ABSTRACT

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ABSTRACT

Recently a growing literature studied the possibility of beneficial brain drain (BBD) through stimulating domestic human capital formation. The first essay explores a new and potentially more important mechanism of BBD through return migration within a framework of Romer-Jones R&D-based endogenous growth. A key premise is that skilled emigrants may return to the home country to seek entrepreneurial opportunities given a suitable domestic business environment and bring back new knowledge from abroad. Surprisingly, under fairly general conditions, the model predicts that benefits from knowledge gain through return migration can overweigh the loss from brain drain in the long term, leading to eventual convergence. A numerical example is provided to calculate the speed of convergence. Available emigration data from the US and New Zealand are supportive of the positive effect of skilled return migration on economic growth.

By calibrating a parsimonious Solow model augmented by natural resources, the second essay offers a simple explanation of the "labor scarcity paradox" during the process of America's catching up with Britain, which static models have difficulties in accounting for so far. A numerical simulation mimics the US overtaking the UK around 1900 in per capita GDP.

The Needham puzzle asked why China lagged technologically in the modern world despite its impressive lead in premodern time. Existing explanations fall into two categories, demand failure or supply failure. The third essay discusses and dismisses two

supply-side hypotheses based on scientific revolution or rent seeking and proposes that the lack of formal legal institutions such as patent protection is an important missing link.

A Poisson regression and a negative binomial regression are applied to two datasets of major invention counts for the US and 14 Western European countries during 1750-1950 and 1590-1900 respectively. The data point to a significant positive effect of patent laws on invention rates, after controlling for each country's economy size. This result is robust in different specifications of cross-country fixed effects and/or random effects models and after dropping the UK and the US from the sample.

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THREE ESSAYS IN GROWTH AND DEVELOPMENT

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure

Page

LIST OF APPENDICES

Appendix Page

CHAPTER I

BRAIN DRAIN, KNOWLEDGE GAIN AND CONVERGENCE

Introduction

The conventional view about brain drain is that it is bad for the home country. By definition brain drain means the exodus of human capital from a poor country to a rich country. Insofar as human capital is important for economic development (Lucas 1988), brain drain without any positive "feedback" may contribute to a "poverty trap." From the perspective of the sending country, it is a lost investment that makes those left behind worse off and may reduce both the home economy's growth rate and income level (see for example, Bhagwati and Hamada, 1974). A natural policy implication is to restrict the outflow of talented nationals by taxation or other means.

How extensive is brain drain? Carrington and Detragiache (1999) showed that for most countries, people with a tertiary education have the highest migration rate. Docquier and Marfouk (2005) estimated that the stock of skilled emigrants in OECD countries in year 2000 is high in the Philippines (1.13 million), India (1.04 million), Mexico (0.92 million), China (0.82 million) and Vietnam (0.51 million), and in relative terms (in proportion to the educated labor force), the emigration rates exceeds 80% in small countries such as Guyana, Jamaica, Haiti, Grenada and St. Vincent. The rate of skilled migration exceeds 50% in the following five African countries: Cape Verde, Gambia, Seychelles, Mauritius and Sierra Leone. It is worth noting that developing countries with large stocks of skilled emigrants may exhibit low rates of emigration. This is obviously the case of India (4.3%), China (3.8%), Indonesia (2.1%) and Brazil (2.2%).

However, even casual observations suggest that most foreign students in the US are from fast-growing economies, such as China, India, South Korea, Taiwan and so on. Can brain drain ever be beneficial? Some recent studies have explored the causation from brain drain to faster growth in the home country (Mountford, 1997; Stark et al., 1997, 1998). The hypothesis is that the opportunity to emigrate raises the returns to human capital investment (i.e., education or professional training) in the home country. The very existence of brain drain therefore raises the pay-off from education, giving an additional incentive for more people to get better education. If this ex ante investment effect outweighs the ex post loss of human capital, then "beneficial brain drain" (BBD) occurs. Beine et al. (2001, 2003) offered the first empirical support that this may not be a mere theoretical curiosity.

But how important this particular form of BBD is empirically is still in doubt. One critical assumption in this BBD literature is that the return to human capital investment is very low in developing countries. The possibility of emigration enhances this return to schooling. However, it seems that the reality in developing countries is that many people cannot afford the cost of education despite plenty of motivation. For example, Psacharopoulos (1985) showed that the returns to human capital investment are typically *higher* in developing countries than in advanced countries.

This essay proposes a new and potentially more important mechanism of BBD through return migration. So far, the contributions of return migration to economic growth have largely been ignored in the literature (Santos et al., 2003, is a notable exception) because return migration is usually very small. For example, Liao and Tang (1984) found that one fifth of undergraduates in the field of science and technology in Taiwan went abroad and only 10% of them returned after completing their study. This is understandable due to the huge income gaps between developing and developed countries. According to World Bank,[1] in 2005, the US per capita GDP is 6 times that of China, 12 times that of India, and 40 times that of Congo. Even compared with those newly industrialized countries in East Asia, such as South Korea, the US per capita GDP is twice as high. Although the income gap between skilled labor in developed versus developing countries may be smaller, it is certainly still sizable, which is a major cause in the recent rise of outsourcing. Therefore, only a small portion of emigrants, presumably those hardcore patriots, ever returns. However, being insensitive to economic incentives, these hardcore patriots are not interesting subjects for economic analysis.

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[1] Numbers are computed from data taken from the World Bank's website at www.worldbank.org/data/quickreference/quickref.html.

Nevertheless, this paper argues that even a small percentage of return migration can make a big difference. The logic is simple. For example, if only one person returns among 10 emigrants, then there is a net loss of 9 units of human capital at the face value. But this very person who returns is very likely to bring back new ideas or technologies from an advanced foreign country. Because research and development (R&D) is typically expensive, it may be the case that even if all 10 units of human capital stay home to engage in closed-door R&D, they may not be as productive as what the single returning migrant can bring back from abroad. After all, it is usually much cheaper to borrow technologies from abroad than to re-invent everything from scratch locally. Prominent examples of beneficial brain drain through return migration include Taiwan and Israel and recently India and China. In 1980, the Taiwan government established the Hsinchu Science-based Industrial Park to specifically attract overseas talents, which has become known as the Taiwanese "Silicon Valley."

Take the example of Taiwanese immigrant Miin Wu who arrived in the US in the early 1970s to pursue graduate training in electrical engineering. After earning a doctorate from Stanford University in 1976, Wu saw little use of his new skills in economically backward Taiwan and chose to remain in the US. He worked for more than a decade in senior positions at Silicon Valley-based semiconductor companies including Siliconix and Intel. By the late 1980s, Taiwan's economy had improved dramatically, and Wu decided to return. In 1989 he started one of Taiwan's first semiconductor companies, Macronix Co., in the Hsinchu Science-based Industrial Park. Macronix went public on the Taiwan stock exchange in 1995 and in 1996 became the first Taiwanese company to list on NASDAQ. It is now the sixth biggest semiconductor maker in Taiwan, with more than $300 million in sales and some 2,800 employees (Saxenian, 2002).

Motivated by this class of returning-entrepreneur phenomena, this paper makes a key assumption that overseas students and skilled professionals return to seek entrepreneurial opportunities in their home countries. In this way, their incomes are only limited by the profits of their "high-tech" firms and are free from the constraint of the huge unfavorable wage gaps between the developing and the developed countries. Their firms' profitability in turn depends on how friendly the business environment is, which offers a number of policy instruments for the home country, such as tax breaks, less corruption or regulations, better infrastructure, and so on.

Certainly, returning professionals who didn't become entrepreneurs may also play an important role in speeding up their native country's human capital accumulation, especially those who work in the education sector. But this doesn't happen very often, especially when the income gap is very large. Even when it happens, it is more likely due to noneconomic factors such as home consumption bias. Santos et al. (2003) provides such a model where temporary emigrants' home consumption bias[2] is low enough that they would emigrate in the first place, but after accumulating human capital abroad, their home consumption bias is high enough that they prefer to return to their home country. In this way, the knowledge/technology gap between the developing and developed countries would shrink to a steady-state gap, but it won't disappear. So the

[2] An alternative interpretation is the ability to learn or accumulate human capital in a foreign country.

mechanism of BBD in Santos et al. (2003) does not imply convergence even in the long run.

In this paper, we focus on returning entrepreneurs who are not constrained by how big the income gap is or the magnitude of their home consumption bias, at least in principle. Since we can't model everything all at once, we ignore those nonentrepreneur returning professionals. Surprisingly, this BBD mechanism through returning entrepreneurs as developed in this paper does imply convergence under very general conditions.

A Framework of R&D-Based Endogenous Growth

Traditional analysis of brain drain usually focused on its impact on the sending country's stock of human capital and income level and was not explicit about its growth effect. We depart from the traditional approach by focusing on the long-run growth effect instead, which is arguably more important than short-run loss or gain of human capital or income level. Clearly, an exogenous growth model is unsuitable for such a task, since the growth rate is fixed and exogenous by definition. Turning our attention to endogenous growth models, there are basically two types of endogenous growth models. The first type focuses on human capital as an engine of growth (Lucas, 1988; Rebelo, 1991) and an escape from the diminishing return to physical capital. However, given the amount of knowledge in a society, the long-run growth rate of human capital per capita can be nothing but zero (Romer, 1990). An approach along this line (e.g., Santos et al. 2003) would have to rely on delicate parameter configurations to explain why migrants would ever want to return to their home country after having accumulated more human capital abroad.

The second type of endogenous growth model focuses on knowledge creation through explicit R & D (Romer, 1990; Aghion and Howitt, 1992; Jones, 1995). Technically, this paper is based on the R&D-based endogenous growth models pioneered by Romer (1990), with an important modification by Jones (1995) to remove the counterfactual scale effect (i.e., growth rate doubles with the doubling of R&D input). Whether R&D-based growth models are appropriate for describing developing economies is a question. After all, they were initially created to explain the growth of advanced economies. In principle, there are only two ways to create new knowledge in a closed economy: through costless learning by doing or through purposeful, costly R & D. History shows that learning by doing itself is not a sustainable engine of growth. For example, China stagnated despite its large population to engage in learning by doing (Lin, 1995). It is now almost a consensus that R&D is the engine of modern growth. In any case, the developing country's R&D sector shall be mostly viewed as an R&D *imitation* sector dedicated to study and adapt foreign technology to its own factor endowments and local environment. As such, the developing country's R&D imitation activity may not be fully included in the standard R&D statistics.

Consider a developing country and a developed country described by a model similar to Jones (1995). The differences between these two countries are *threefold*: the developing country has a lower initial human capital stock, a lower initial level of knowledge, and a less efficient government in providing law and order, infrastructure, etc. (the meaning of which will be made precise below) than the developed country.

Let's focus on the developing country first. There are three sectors in the economy populated by infinitely lived agents: a perfectly competitive final goods sector, an intermediate goods sector with a continuum of monopolists, and an R & D sector. Time is continuous. In contrast to Romer (1990) and Jones (1995), we assume that labor is used in the final goods sector only, and human capital is used in the R & D sector only. This simplification is justified since we are not concerned with allocating human capital between the final goods sector and the R & D sector. Both labor and human capital are assumed to grow at the constant rate of n.[3] The production of the final goods sector is given by the "love-of-variety" functional form:

$$Y = \theta L^{\alpha} \int_0^A x_i^{1-\alpha} \, di \ , \tag{1.1}$$

where Y is the final good, L is the labor force, x is the intermediate good indexed by $i \in [0, A]$, A is the current knowledge level (also the current number of intermediate

[3] As the developing country assimilates more knowledge from abroad through returning entrepreneurs, its rate of human capital accumulation may also speed up. This would even strengthen the main result in this paper. For simplicity, we ignore this possibility.

capital goods), and $\theta \in (0,1]$ is an indicator of government efficiency. Apparently, inefficient governmental provision of good institutions and infrastructure lowers firms' output. For the advanced country, θ is set to 1.

We normalize the price of final goods to unity and let p_i be the rental price of intermediate good x_i. The profit of the i^{th} final good firm is given by:

$$\pi_i = \theta L^{\alpha} \int_0^A x_i^{1-\alpha} di - \int_0^A p_i x_i di \,. \tag{1.2}$$

Then profit maximization implies an inverse demand function for intermediate good:

$$p_i = \theta(1-\alpha)L^{\alpha} x_i^{-\alpha} \qquad \forall i \in [0, A]. \tag{1.3}$$

The intermediate sector is composed of an infinite number of firms on the interval $[0, A]$. Each of them is a monopolist in providing a particular intermediate good x_i, after obtaining a patent from the R & D sector. Suppose an intermediate firm rents generic capital goods from consumers at the interest rate r and then transforms them into intermediate goods on a one-to-one basis, discounted by the government efficiency index θ. Then its profit maximization problem is:

$$\max_{x_i} \; p_i \theta x_i - r x_i \,, \tag{1.4}$$

$$\text{s.t. } p_i = \theta(1-\alpha)L^{\alpha}x_i^{-\alpha}.$$

Anticipating the conditional demand from the final goods sector, this monopolist's optimization problem can be readily solved to yield:

$$\overline{p}_i = \overline{p} \equiv \frac{r}{\theta(1-\alpha)} \qquad \forall i \in [0, A], \tag{1.5}$$

$$\overline{x}_i = \overline{x} = [\theta(1-\alpha)]^{\frac{2}{\alpha}} r^{-\frac{1}{\alpha}} L \qquad \forall i \in [0, A], \tag{1.6}$$

$$\overline{\pi}_i = \overline{\pi} = \alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}} \theta^{\frac{2}{\alpha}} r^{1-\frac{1}{\alpha}} L \qquad \forall i \in [0, A], \tag{1.7}$$

where $\overline{p}$, $\overline{x}$, and $\overline{\pi}$ denote the corresponding optimal values. By symmetry, all intermediate goods would be set at the same monopoly mark-up price, $\overline{p} = \frac{r}{\theta(1-\alpha)}$, and provided at the same amount $\overline{x}$, which grows proportionally with the labor force *L*. Each monopolist in the intermediate sector also makes the same profit, $\overline{\pi}$, which grows proportionally with the labor force but depends positively on government efficiency.

Finally, new knowledge is created in the R & D sector according to:

$$\dot{A} = \theta\delta H^{\lambda} A^{\phi}, \tag{1.8}$$

where δ is a constant coefficient, *H* is the human capital stock, $0 < \lambda < 1$ and $\phi < 1$.

Note that the restriction of $\phi < 1$ is necessary to remove the counterfactual scale effects in Romer (1990), where growth rate is proportional to the level of human capital. The compensation to human capital w_H is determined through the zero profit condition of a typical R & D firm.

$$\pi_{RD} = P_A \theta \delta H^{\lambda} A^{\phi} - w_H H = 0, \tag{1.9}$$

$$w_H = P_A \theta \delta A^{\phi} H^{\lambda - 1}, \tag{1.10}$$

where P_A is the price or market value of a new patent. Correctly foreseeing an intermediate monopolist's profit flow $\{\overline{\pi}_t\}_o^{\infty}$, the R & D firm sets P_A to extract the present value of this profit flow since the intermediate sector is monopolistically competitive. Viewing the purchase of a new patent as an investment, then the "no arbitrage condition" between different investment opportunities requires:

$$r = \frac{\overline{\pi}}{P_A} + \frac{\dot{P}_A}{P_A}. \tag{1.11}$$

From equation (1.11), it is easy to see that on the balanced growth path, the steady-state growth rate of P_A must equal the growth rate of an intermediate firm's profit, which is the same as the labor force growth rate *n*, i.e., $\frac{\dot{P}_A}{P_A} = n$. This can be proven by contradiction. If $\frac{\dot{P}_A}{P_A} < n$, then the term $\frac{\overline{\pi}}{P_A}$ in (1.10) will blow up, and there will be no steady state. On the other hand, if $\frac{\dot{P}_A}{P_A} > n$, then $\bar{\pi} = 0$ in the steady state, and all patents become worthless. Therefore, in equilibrium P_A grows at the same rate as $\bar{\pi}$ and is given by,

$$P_A = \frac{\bar{\pi}}{r - n}. \tag{1.12}$$

The consumer part of this model is the same as in the standard neoclassical growth model. A representative consumer maximizes:

$$\int_0^{\infty} \frac{c_t^{1-\sigma} - 1}{1-\sigma} e^{-(\rho - n)t} dt, \tag{1.13}$$

which leads to the usual equilibrium condition of consumption growth:

$$\frac{\dot{c}}{c} = \frac{r - \rho}{\sigma}. \tag{1.14}$$

The R & D equation (1.8) pins down the growth rate of A. Rewrite equation (1.8):

$$\frac{\dot{A}}{A} = \frac{\delta \theta H^{\lambda}}{A^{1-\phi}}. \tag{1.15}$$

Given this model, it is easy to show that there exists a globally stable balanced growth path (i.e., H^{λ} and $A^{1-\phi}$ must grow in the same rate), and the steady-state growth rates of knowledge, per capita output, per capita capital and per capita consumption are all the same and proportional to the human capital growth rate n:

$$g = \frac{\lambda n}{1-\phi} = g_y = g_k = g_c \,. \tag{1.16}$$

The steady-state interest rate is determined through equation (1.14):

$$r = \rho + g\sigma \,. \tag{1.17}$$

Combining equations (1.10), (1.12) and (1.16), it is easy to show that the human capital compensation, w_H, also grows at the rate of g.

Brain Drain, Knowledge Gain and Convergence

With the above framework, we are now in a position to explore the issues related to brain drain and reverse brain drain by extending it to a two-country setting. For simplicity, we ignore international trade. We also exclude the possibility of international capital mobility so that the interest rate is determined inside each economy. For countries at a low level of development, their financial markets may not be very developed and may be heavily regulated by their governments, hence less integrated into the world capital market. However, during the process, a developing country catches up with advanced economies; this assumption may become problematic. At the other extreme, if we assume perfect capital mobility such that the interest rate of a "small, open" developing country is completely determined by the interest rate of a "large, open" developed country (say, the US), then there are several paradoxical results as shown by Barro and Sala-i-Martin (2004) within a neoclassical growth framework.[4] These paradoxes include infinite speed of adjustment of the capital stock, consumption per efficiency unit tending to zero asymptotically, and asset per efficiency unit becoming negative asymptotically. Some sorts of constraints on international credits are needed to resolve these paradoxes. But the credit-constrained open economy again behaves like a closed economy in some sense (Cohen and Sachs, 1986; Barro et al., 1995). In reality, we rarely see that a country's interest rate is completely determined by the "world interest rate." As long as there is a significant component of the domestic interest rate that is determined inside its own economy, our assumption of zero international capital mobility helps abstract us from unnecessary international finance complications, so that we can focus on delivering our central message about the transmission of knowledge through return migrants.

First, consider the case of autarky as a benchmark. In autarky, a country's growth rate depends on its human capital growth rate and other exogenous parameters. So these two

[4] The reduced form of an R&D-based endogenous growth model is still a neoclassical growth model, after the endogenous rate of technical change is pinned down.

countries will grow at the same rate, $\frac{\lambda n}{1-\phi}$,[5] but the developing country would never catch up with the developed country due to a lower initial knowledge level and lower initial human capital stock. Therefore the proportional gap in absolute income level remains constant, as illustrated in Figure 1.

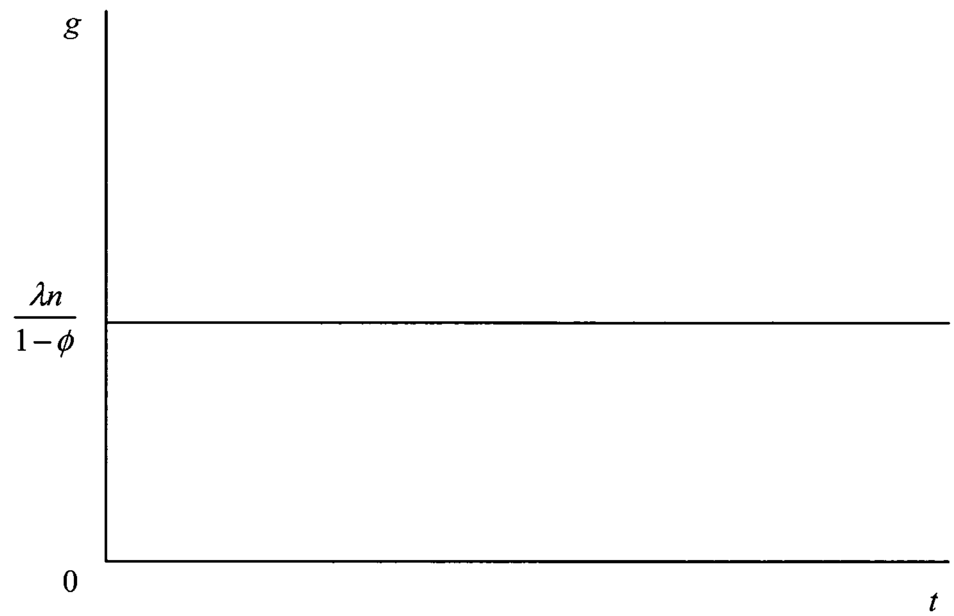

Figure 1. Growth rates under autarky.

Second, consider open economies with brain drain but without the possibility of return migration.

[5] This is consistent with the fact that the growth rates of developed and developing countries are roughly the same in the twentieth century (see Barro and Sala-i-Martin, 2004), with the growth rates of developing countries sometimes slightly higher (perhaps thanks to assimilating knowledge from developed countries).

Compared with autarky, the situation apparently just gets worse from the perspective of the developing country. We assume that only human capital is qualified to migrate (so nonhuman capital labor force cannot migrate). Furthermore, we assume that a fixed proportion β of the developing country's human capital emigrates to the developed country at any point in time. The fixed emigration proportion β can depend upon both the developed country's policies (e.g., immigration or visa quota) and the developing country's policies (e.g., political restriction or penalty fee).

Assuming a fixed emigration ratio of β is a sensible first approximation because if β is increasing unbounded towards unity, then it would eventually exhaust all of the sending country's human capital stock (possibly also exceed the capacity of the receiving country to accept immigrants), which is an extreme situation. If β is increasing but approaches an upper bound strictly less than unity asymptotically, then we would just relabel this upper bound β, since we are most interested in the long-run effects. Similar arguments can be made for the case where β is monotonically decreasing. Therefore, a fixed β is a suitable assumption for long-run analysis.

Therefore, at time *t*, the outflow of "brain drain" is $\beta H_0 e^{nt}$, where H_0 is the developing country's human capital stock at time 0, which grows at the constant rate of *n*.

Skilled migrants are chosen randomly by the destination country through lotteries. The decision to emigrate is obvious. Any "human capital" who wins the lottery to go abroad will go. Without loss of generality, we ignore the one-time fixed cost of migration. In this case, although the human capital growth rate is still the same, the home country is left with an even lower initial stock of human capital. The opposite happens to the developed country. While its human capital growth rate is still the same (since both the native component and the immigrant component grow at the same rate), its absolute level jumps to a higher level. Therefore, the gap between these two countries would become even bigger during transition dynamics, although in the steady states they continue to grow at the same rate (see Figure 2).

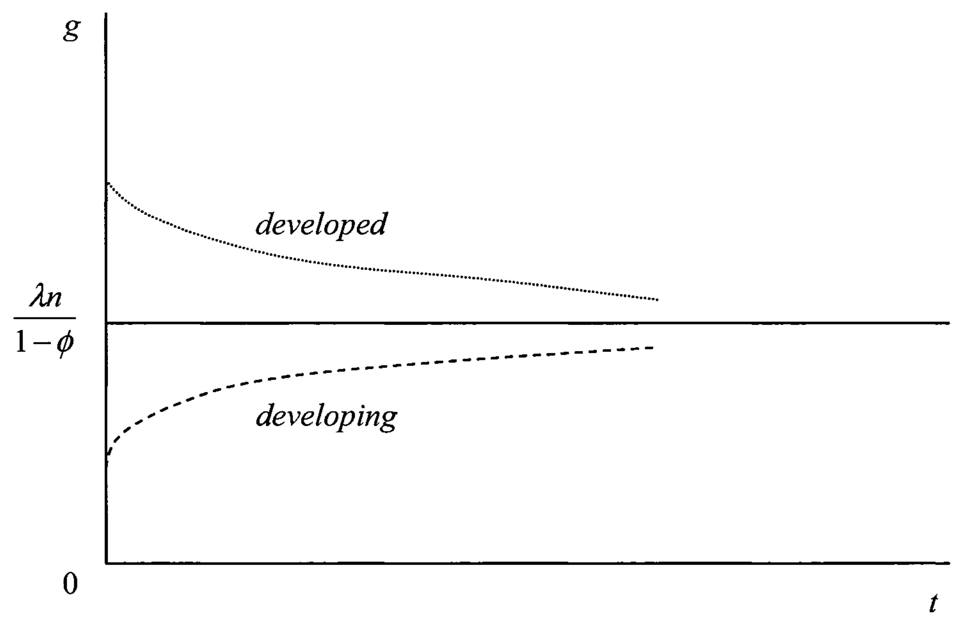

Figure 2. Growth rates with brain drain, but without return migration.

Third, consider the most interesting case of brain drain with the possibility of return migration. As discussed earlier, it is not realistic to expect return migration to happen because of shrinking income gaps (often 10 times or more) between these two countries. To make it worse, adverse selection due to asymmetric information can also deter return migration; i.e., domestic employers do not have enough information to distinguish more capable return migrants from less capable ones than foreign employers (Kwok and Leland, 1982). However, after being exposed to the advanced economy and its state-of-the-art knowledge and technology, emigrants now have the option to bring a new design to manufacture in their home country. Due to the huge gap in the knowledge level, there are certainly many such opportunities to exploit. For simplicity, it is assumed that while reaping the monopolistic profit flow given by equation (1.7), they do not need to pay any licensing or patent fee to the inventors in the developed country. This is without loss of generality. One reason is that all patents have only limited lengths. For example, it is 17 years in the US. Second, paying a certain licensing fee or incurring some imitation cost will not weaken this model as long as it is cheaper than reinventing the technology in the developing country.

On the other hand, human capital who stayed in the developing country (i.e., those who have never gone abroad) cannot utilize foreign knowledge because of asymmetric information and the fact that much technical know-how is tacit and it takes a trip and an extended stay in the developed country (either as a student or an employee) to grasp this implicit knowledge. In this way, former emigrants become important potential messengers of technological transmission, as the new designs they brought back directly add to the developing country's knowledge base. Compared with foreign direct investment, returning entrepreneurs do not face the language, cultural and social barriers that usually apply to foreign investors.

First consider the effect of brain drain on the destination country. Since it doesn't change the developed country's human capital growth rate, it has no impact on its long-run growth. However, it does give a positive shock to the developed economy to jump to a higher growth path during the transition dynamics. Therefore, everybody in the advanced economy would be better off in the long run, despite some short-term pain due to structural adjustment (i.e., a higher human capital stock would temporarily depress skilled labor's market compensation. See, for example, Borjas, 2006). This was one reason why Gary Becker (2005) in a recent article in *Wall Street Journal* called for a more friendly immigration policy towards foreign professionals.

Now consider the emigrants' decision to return or not. Abstracting from all social and cultural factors, we focus on comparing the income streams that either staying in the developed country or returning home can bring.

Now consider an emigrant who arrives at the developed country at time t. After a fixed period of learning and being exposed in the advanced economy, he or she is eligible to return to his or her home country as an entrepreneur. To tell a clean story, we set this fixed period to zero without loss of generality. Setting it to a positive period, say 5 years or 10 years, will not change the long-run growth effects that we are most concerned about but will make the notation a bit messy. Furthermore, it is not important to explicitly specify what migrants do during their stay in the advanced country. It doesn't matter whether they go to school or work in the R&D sector; it suffices for our purpose that they would gain enough technical know-how so as to bring back a new product design if they choose to, and by the time they make a return migration decision, they are "good" enough to work in the R&D sector of the advanced country if they choose to. Therefore, if this emigrant stays in the developed country, his income stream is given by:

$$\hat{w}_s = \hat{w}_0 e^{\hat{g}s}, \tag{1.18}$$

where s is a time variable, ^ indicates the developed country, and $\hat{w}_0$ is the developed country's compensation to human capital in the R&D sector at time 0. Notice that equation (1.18) is only an approximation. With "brain gain," the advanced economy's short-term growth rate is going to be higher than the steady-state growth rate $\hat{g}$. However, since the developing country only has a smaller human capital stock to begin with, and only a small portion of it is "siphoned off" to the developed country, this approximation is sufficient for our purpose to the extent that few emigrants would decide not to return simply because there are many fellow countrymen in the developed country to make his prospect of future staying much brighter. The current "subjective" value of this income stream at time t if staying is:

$$CV_{ST} = \eta \int_t^{\infty} \hat{w}_0 \frac{e^{\hat{g}s}}{e^{\hat{r}(s-t)}} ds = \eta \frac{\hat{w}_0 e^{\hat{g}t}}{\hat{r} - \hat{g}}, \tag{1.19}$$

where $\eta \in (0,1)$ is introduced to account for home consumption bias,[6] which is a common assumption in the micro literature of migration (see, for example, Djajic and Milbourne, 1988). If an emigrant chooses to return as an entrepreneur, his income stream is given by the profit flow given in equation (1.7) in principle. However, we do not observe everybody return because not everybody can become a good entrepreneur. Therefore, we assume that each unit of human capital is born with an index of entrepreneurial ability $a \in U[0,1]$, which is drawn randomly from a uniform distribution between 0 and 1. There is no self-selection bias of different entrepreneurial endowment since all human capital would prefer to emigrant if given the chance with or without a high entrepreneurial ability, since emigration implies a higher present value of income whether the migrant stays in the advanced country temporarily or permanently. It is further assumed that the profit flow that returning human capital is able to achieve is proportional to their entrepreneurial ability. Specifically, the flow of profit accruing to a typical returning entrepreneur is given by:

$$\pi_s = a\alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}} \theta^{\frac{2}{\alpha}} r^{1-\frac{1}{\alpha}} L_s = \pi_0 e^{ns}, \tag{1.20}$$

where $\pi_0(a,\theta) \equiv a\alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}} \theta^{\frac{2}{\alpha}} r^{1-\frac{1}{\alpha}} L_0$ depends on both a and θ positively. We assume perpetual monopoly, and hence this profit flow lasts forever. This assumption can be easily relaxed to model the erosion of monopoly power over time as proposed by Barro and Sala-i-Martin (2004), but it will not change the basic flavor. Hence the current

[6] This is not a critical assumption. We put it here to be consistent with the micro migration literature.

value of his profit flow at time t is:

$$CV_{RT} = \int_t^{\infty} \frac{\pi_0 e^{ns}}{e^{r(s-t)}} ds = \frac{\pi_0(a,\theta)e^{nt}}{r-n}. \tag{1.21}$$

Assume that for an individual with full entrepreneurial ability (i.e., $a=1$) and a sufficiently high value of θ the current value of returning is greater than staying, i.e., $CV_{RT} > CV_{ST}$. This is a sensible assumption since a capable returning entrepreneur may make more money than an average wage-earner in the developed country. Alternatively, he could stay in the developed country to become an entrepreneur. But given our model setup, he would not make a positive profit by doing so, whether he owns an R&D firm or an intermediate firm.

Obviously, when $a=0$, $CV_{RT} = 0 < CV_{ST}$. Then by the intermediate value theorem, there exists an $a_t^* \in (0,1)$ such that individuals with a_t^* entrepreneurial endowment will feel indifferent between staying and returning, i.e.:

$$\frac{\pi_0(a_t^*,\theta)e^{nt}}{r-n} = \frac{\eta \hat{w}_o e^{\hat{g}t}}{\hat{r}-\hat{g}}. \tag{1.22}$$

Then every emigrant with $a \geq a_t^*$ will return, whereas the rest stay. Note the dependency of a_t^* on time in general. This is because while π_s grows at the rate of n, $\hat{w}_s$ grows at the rate of $\hat{g}=\frac{\lambda n}{1-\phi}$. Only when $\lambda+\phi=1$, does $n=g$, and a^* is fixed over time unless government efficiency θ changes (assuming that interest rates are fixed in the steady state by the relation $r=\rho+g\sigma$). If $\lambda+\phi<1$ (the most plausible case as argued below), then $n>\hat{g}$, and the growth of π_s continues to outpace $\hat{w}_s$, reducing a^* over time to zero at the rate of $e^{-(n-\hat{g})t}$ so that in the limit everyone returns. (During this process the developing country's income converges to that of the developed country as shown below.) This is consistent with the stylized fact that as the income gap shrinks, more and more migrants choose to return to their home country. When the income gap is sufficiently small, then everybody returns or they would not emigrate in the first place (imagine the case of Japan).

On the other hand, if $\lambda+\phi>1$ (an unlikely case), then $n<\hat{g}$, and the growth of π_s continues to lag behind $\hat{w}_s$, increasing a^* to unity over time, so that $CV_{RT}<CV_{ST}$ and nobody returns.

Notice that a^* depends inversely on government efficient parameter θ, which depends on the fixed costs of setting up a business (getting licenses, etc.), infrastructure, the financial system and capital markets, tax breaks, governmental regulations, corruption, special economic zones, business environment and so on. Note that the dependency is very sensitive, and a small change in θ can bring about a large change in a^*. For example, in the benchmark case of $\alpha=\frac{2}{3}$, a^* is proportional to $\frac{1}{\theta^3}$.

Therefore, the flow of return migration at time t is $(1-a^*)\beta H_0 e^{nt}$. Recall that at time t, the outflow of "brain drain" is $\beta H_0 e^{nt}$, leaving $(1-\beta)H_0 e^{nt}$ units of human capital in the developing country. For simplicity, we assume that each returning entrepreneur brings back one new design of capital good without loss of generality. Hence, the growth of knowledge in the home country consists of two parts: indigenous production through R&D with remaining human capital and borrowed technology through skilled return migration:

$$\dot{A} = \delta\theta\left[(1-\beta)H_0 e^{nt}\right]^{\lambda} A^{\phi} + (1-a^*)\beta H_0 e^{nt}. \tag{1.23}$$

Notice that both effects of "brain drain" and "knowledge gain" are reflected in equation (1.23). With this new equation of knowledge growth, will the developing country eventually catch up with the developed country? This is the focus of the remaining analysis.

Rewrite equation (1.23) in terms of percentage growth:

$$\frac{\dot{A}}{A} = \frac{\delta\theta\left[(1-\beta)H_0 e^{nt}\right]^{\lambda}}{A^{1-\phi}} + \frac{(1-a^*)\beta H_0 e^{nt}}{A}. \tag{1.24}$$

It is easy to see that on the righthand side of equation (1.24), the first term grows at the rate of $\lambda n-(1-\phi)g$ and the second term grows at the rate of $n-g$ (treating a^* as a constant for the moment).

Case 1. $\lambda+\phi<1$ (the most plausible case)

In this case, the second term in (1.23) dominates the first term, since for $0<\lambda<1$:

$$n-g>\lambda(n-g)>\lambda n-(1-\phi)g\,. \tag{1.25}$$

Furthermore, as argued earlier, under $\lambda+\phi<1$, a^* tends to zero in infinity, and the term $(1-a^*)$ goes to 1 in infinity, so it wouldn't give us any trouble. Then the steady-state growth rate of knowledge in the developing country is determined by the second term:

$$g=n \tag{1.26}$$

which assures that the developing country will *eventually* grow faster than the developed country until it catches up, since:

$$g=n>\hat{g}=\frac{\lambda n}{1-\phi}\,. \tag{1.27}$$

Essentially, under $\lambda+\phi<1$, the R & D production function is not very "powerful" so that benefits from "knowledge gain" are *eventually* enough to outweigh losses from "brain drain" to assure convergence to the developed country. See Figure 3.

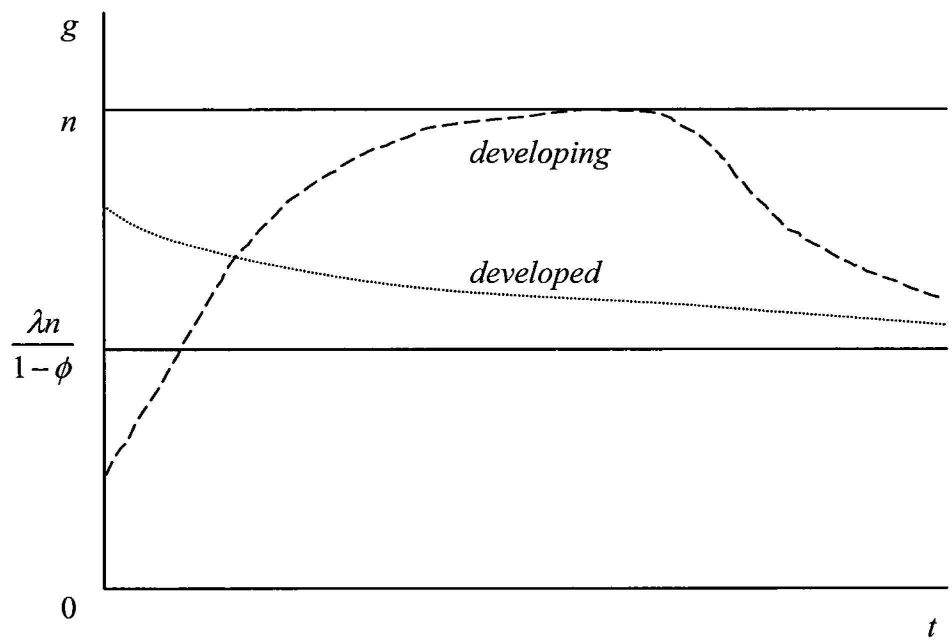

Figure 3. Brain drain with return migration under $\lambda+\phi<1$.

But what happens in the short run? It is ambiguous. The developing country's growth rate may immediately accelerate or first decelerate and then accelerate, depending on government efficiency θ and emigration rate β, among others. From equation (1.23), we can see that a positive short-run growth effect requires:

$$(1-a^{*})\beta\left(H_0e^{nt}\right)^{1-\lambda} > \delta\theta\left[1-(1-\beta)^{\lambda}\right]A^{\phi}. \tag{1.28}$$

Also note the government efficiency θ may be endogenous and depends positively on the rate of return migration $(1-a^{*})$, as more returned migrants wield influence and persuasion or even take up government posts directly.

Why is $\lambda+\phi<1$ the most plausible case? Recall that λ and ϕ are parameters in the knowledge production function $\dot{A}=\theta\delta H^{\lambda}A^{\phi}$ (equation 1.8).

(1) As pointed out before, $0<\lambda<1$, which occurs when there is either duplication in research efforts (e.g., several firms engage in the same research), or as the size of R & D personnel grows, its average quality declines (e.g., Ph.D.s from the top 10 universities are of higher quality on average than Ph.D.s from the top 100 universities).

(2) As mentioned earlier, $\phi<1$ is necessary to eliminate counterfactual strong scale effects. Actually, $\phi<0$ represents the case of "fishing out"; i.e., as those easy discoveries are made first, it becomes increasingly difficult to create new knowledge. On the other hand, $\phi>0$ represents a positive external effect, i.e., old knowledge aids in the production of new knowledge. Therefore a natural benchmark is $\phi=0$, without any positive or negative external effects. If $0<\lambda<1$ and $\phi=0$ or is sufficiently close to 0, then $\lambda+\phi<1$.

(3) $\lambda+\phi<1$ corresponds to the case of decreasing returns to scale when both human capital and current knowledge are considered inputs. On the other hand, $\lambda+\phi>1$ signifies increasing returns to scale (the possibility of $\lambda+\phi=1$ will be discussed next), which makes the knowledge production function so "powerful" that "strange" things happen (e.g., as discussed above, "nobody returns in the limit").

(4) λ and ϕ are called by Romer (1990) "philosophical parameters" that are virtually impossible to estimate separately. However, a combination of them may be estimated. For example, Alcala and Ciccone (2002) estimated $\frac{\lambda}{1-\phi}=0.20$, which implies that $\lambda+\phi<5\lambda+\phi=1$. Hall and Jones (1999) obtained an even lower estimate in which $\frac{\lambda}{1-\phi}=0.05$, which implies $\lambda+\phi<20\lambda+\phi=1$. It appears that $\lambda+\phi$ is not only less than 1, but actually far less than 1.

For the above reasons, we will restrict our attention to the case $\lambda+\phi<1$ for practical purposes. Furthermore, it is worth pointing out that although an eventual catch-up and convergence is inevitable under this scenario, it may take a very long time, and its impact on the developing country's short-term growth rate is ambiguous. Whether brain drain can become beneficial immediately or how soon it takes depends critically on the rate of return migration $(1-a^{*})$, upon which government efficiency θ exerts a big influence. In the next section, we conduct a numerical example on the speed of convergence to demonstrate this dependency explicitly.

Also notice that if government efficiency θ is low, then many emigrants would stay in the developed country "permanently" (or only return at a distant date). Over time, its total size can become quite large. For example, by the end of the 1990s, Chinese and Indian engineers were running 29% of Silicon Valley's technology business, and the pace of immigrant entrepreneurship has accelerated dramatically in the past decade (Saxenian, 2002). The power of this international reserve of human capital can be unleashed if the government of the developing country can improve its efficiency θ, which seems to be the case for India and China recently.

Notice that divergence is still possible under $\lambda + \phi < 1$ at least for a period of time. First of all, if nobody returns $(1 - a^* = 0)$, then it is definitely a divergence like in Figure 2. Second, if only a small number of people return, $1 - a^* \approx 0$ (or too small), then the developing country would suffer initially, until the second term of return migration starts to dominate the first term in absolute terms. Third, for the convenience of analysis, we have ignored the time period that an emigrant needs to stay in the developed country to acquire necessary human capital to become a returning entrepreneur. So during this period (say 5-10 years), the impact on the developing economy would be negative.

Notice that this model predicts convergence, but not leapfrogging. As the developing country gradually catches up with the developed country, it would become increasingly difficult to find a new idea in the developed country that hasn't been imitated in the home country, since $A \approx \hat{A}$. Also, with $A \approx \hat{A}$, the incentive to emigrate also disappears, and this mechanism of "brain circulation" would stop.

Also, if we allow returned skilled labor to go back to the domestic R & D sector, this will give additional boost to the domestic economic growth. Foreign-trained R & D personnel may master more knowledge than their home-groomed colleagues, i.e., like "virtual knowledge" only in their heads since the domestic economy still cannot produce the corresponding intermediate goods.

Case 2. $\lambda + \phi = 1$

In this case, the second term in (1.22) still dominates the first term, since for $0 < \lambda < 1$ we have $n - g > \lambda(n-g) \geq \lambda n - (1-\phi)g$. However, in the steady state, both countries will grow at the same rate since $g = n$ and $\hat{g} = \dfrac{\lambda n}{1-\phi} = n$. During the short-run transitional dynamics, the result is ambiguous.

Case 3. $\lambda + \phi > 1$

In this case, the first term dominates the second term, i.e.:

$$n - g < \lambda n - (1-\phi)g. \tag{1.29}$$

Then the steady-state growth rate is determined by the first term:

$$g = \frac{\lambda n}{1-\phi}. \tag{1.30}$$

This can be readily proven by contradiction. Under $\lambda + \phi > 1$, if the second term dominates the first term instead, then $n - g > \lambda n - (1-\phi)g$ and $g = n$ hold simultaneously. Combining them together yields $0 > n(\lambda + \phi - 1)$, which contradicts $\lambda + \phi > 1$. Furthermore, as argued before, under $\lambda + \phi > 1$, eventually nobody returns; therefore, $(1 - a^*)$ tends to infinity, making the second term even smaller over time. Equation (1.30) indicates that the developing country will grow at the same rate as the developed country in the long run. However, whether the developing country can still grow faster in the short term and enough to eventually catch up with the developed country is ambiguous. Most likely the income gap would even widen in this case. Because the knowledge production function $\dot{A} = \theta \delta H^{\lambda} A^{\phi}$ is more powerful under $\lambda + \phi > 1$, the damage to new knowledge production is more acute with the loss of human capital through brain drain. To make it worse, our previous analysis shows that given a fixed government efficiency θ, the rate of return migration becomes smaller over time. If the benefits from return migration do not come very fast and sizable, then the developing country may further drift apart from the developed country in terms of knowledge level A; i.e., divergence happens.

The Speed of Convergence: A Numerical Example

In this section, we want to calculate the speed of convergence, i.e., how long it would take for the developing country to catch up with the developed country in terms of the knowledge level, hence per capita income level.

Recall that the fundamental differential equation governing the growth of knowledge in the developing country is:

$$\dot{A} = \delta\theta\left[(1-\beta)H_0 e^{nt}\right]^{\lambda} A^{\phi} + (1-a^{*})\beta H_0 e^{nt}, \tag{1.23}$$

which doesn't admit an analytic solution unless $\phi = 0$, under which (1.23) becomes a first-order linear ordinary differential equation that can be readily solved. Apparently, $\phi = 0$ is not a bad assumption, since it corresponds to the neutrality of old knowledge in the production of new knowledge after balancing the effects of "fishing out" and "standing on giants' shoulders." Although the case of $\phi \neq 0$ can be tackled numerically, it is unlikely to yield much additional insight by the continuity argument. Hence we focus on the case of $\phi = 0$ to estimate the speed of convergence.

For simplicity, we assume the following (standard textbook) calibration values in this exercise. The labor of share of income α is assumed to be $\frac{2}{3}$. The degree of relative risk aversion σ is set to be unity, reducing the period utility function to be logarithmic.

The time discount rate is $\rho = 0.05$, and the growth rate of both the human capital and labor force is $n = 0.02$. The proportion of skilled emigration is set somewhat arbitrarily to $\beta = 0.1$, and the home consumption bias is assumed to be $\eta = 0.5$. With little information about λ, we set $\lambda = 0.8$. This implies that the per capita income growth is about $\frac{\lambda}{1-\phi} = 80\%$ of the population growth rate, which is consistent with stylized facts. We normalize the human capital stock at time zero (H_0) and knowledge stock at time zero (A_0) in the developing country to be unity and set its labor force at time zero (L_0) to be 100, which implies $\frac{H_0}{L_0} = 1\%$. For the developed country, we set $\hat{H}_0 = 5$, $\hat{A}_0 = 20$ and $\hat{L}_0 = 50$, which implies $\frac{\hat{H}_0}{\hat{L}_0} = 10\%$[7] and there is 20 times difference in knowledge and income level initially. Finally, the knowledge production parameter δ is set to be 0.09 to match the initial growth rate in the developed country to its steady-state growth rate. Table 1 summarizes these calibration values.

[7] In 2003, there were 15,689,000 Americans with bachelor's or above degrees in science and engineering, according the National Science Foundation data available at www.nsf.gov/statistics/seind06/c3/tt03-01.htm. In the same year, the American civilian labor force was 146,510,000, according to Bureau of Labor Statistics data available at www.bls.gov. This implies $\hat{H}_0 / \hat{L}_0 = 12\%$ (we assume 10% for simplicity).

Table 1

Calibrating an Example Economy

Parameter Values	Explanation
$\alpha = \frac{2}{3}$	Final good production parameter (labor)
$\delta = 0.09$	Knowledge production parameter[8]
$\lambda = 0.8$	Knowledge production parameter (human capital)
$\phi = 0$	Knowledge production parameter (knowledge)
$\sigma = 1$	Degree of relative risk aversion
$\rho = 0.05$	Time discount rate
$n = 0.02$	Growth rate of human capital and/or labor force
$\beta = 0.1$	Proportion of skilled emigration
$\eta = 0.5$	Home bias discount in consumption
$H_0 = 1$	Developing country's human capital stock at time 0
$A_0 = 1$	Developing country's knowledge level at time 0
$L_0 = 100$	Developing country's labor force at time 0
$\hat{H}_0 = 5$	Developed country's human capital stock at time 0
$\hat{A}_0 = 20$	Developed country's knowledge level at time 0
$\hat{L}_0 = 50$	Developed country's labor force at time 0

[8] δ is chosen to be 0.09 so that $\frac{\dot{\hat{A}}_0}{\hat{A}_0} \approx 0.016$, which matches the equilibrium growth rate.

The above calibration implies $\hat{g} = \dfrac{\lambda n}{1-\phi} = 0.016$, $\hat{r} = \rho + \sigma\hat{g} = 0.056$, and

$r = \rho + \sigma g = 0.07$. (For simplicity, we use the equilibrium value of $g = n$ in this approximation.) Then (1.23) becomes:

$$\dot{A} = 0.09\theta\left[0.9e^{0.02t}\right]^{0.8} + (1-a^*)0.1e^{0.02t}. \tag{1.31}$$

Now we need to determine a^*. From (1.10), we can estimate $\hat{w}_0$:

$$\hat{w}_0 = \hat{P}_{A0}\delta\hat{H}_0^{\lambda-1} = 0.09\times\frac{\hat{\pi}_0}{\hat{r}-n}H_0^{-0.2} = 6.71.$$

From (1.22), we see that a_t^* (the indifference level of entrepreneurial ability between returning and staying) is determined by:

$$a_t^* = \left(\frac{r-n}{\hat{r}-\hat{g}}\right)\frac{\eta\hat{w}_0}{\left(\alpha(1-\alpha)^{\frac{2-\alpha}{\alpha}}\right)\theta^{\frac{2}{\alpha}}L_0e^{(n-\hat{g})t}} = \frac{0.45}{\theta^3e^{0.004t}}. \tag{1.32}$$

It is easy to see that in order for $a_0^* < 1$ (i.e., strictly less than unity for return migration to begin at time zero), it is necessary that $\theta \geq 0.77$. For $0 < \theta < 0.77$, return migration won't happen until time $T(\theta)$, where:

$$T(\theta) = 250(\ln 0.45 - 3\ln\theta). \tag{1.33}$$

For example, if $\theta = 0.5$, then return migration won't start until 320 years later, which is probably not realistic. Therefore, we focus on the case of $\theta \geq 0.77$.

Now we plug this value of a_t^* in (1.32) back into differential equation (1.31):

$$\dot{A} = 0.09\theta\left[0.9e^{0.02t}\right]^{0.8} + (1 - \frac{0.45}{\theta^3 e^{0.004t}})0.1e^{0.02t}. \qquad (1.34)$$

Rearranging, we get:

$$\dot{A} = \left(0.083\theta - \frac{0.045}{\theta^3}\right)e^{0.016t} + 0.1e^{0.02t} \qquad \text{with } A_0 = 1. \qquad (1.35)$$

whose solution is:

$$A_t = \left(\frac{2.81}{\theta^3} - 5.19\theta - 4\right) + \left(5.19\theta - \frac{2.81}{\theta^3}\right)e^{0.016t} + 5e^{0.02t}. \qquad (1.36)$$

If $\theta = 0.8$, then $A_t = -2.66 - 1.34e^{0.016t} + 5e^{0.02t}$.

If $\theta = 0.9$, then $A_t = -4.82 + 0.82e^{0.016t} + 5e^{0.02t}$.

If $\theta = 1$, then $A_t = -6.38 + 2.38e^{0.016t} + 5e^{0.02t}$.

On the other hand, the knowledge level in the developed country is:

$$\hat{A}_t = \hat{A}_0 e^{0.016t} \qquad \text{with } \hat{A}_0 = 20. \qquad (1.37)$$

If $\theta = 0.8$, then the time to catch up t^* is determined by,

$$-2.66 - 1.34e^{0.016t^*} + 5e^{0.02t^*} = 20e^{0.016t^*} \quad \Rightarrow t^*\big|_{\theta=0.8} = 363 \text{ years}. \qquad (1.38)$$

If $\theta = 0.8$, then the time to catch up, t^*, is determined by:

$$-4.82+0.82e^{0.016t^*}+5e^{0.02t^*}=20e^{0.016t^*} \quad \Rightarrow t^*\big|_{\theta=0.9}=336 \text{ years.} \tag{1.39}$$

If $\theta = 1$, then the time to catch up, t^*, is determined by:

$$-6.38+2.38e^{0.016t^*}+5e^{0.02t^*}=20e^{0.016t^*} \quad \Rightarrow t^*\big|_{\theta=1}=315 \text{ years.} \tag{1.40}$$

The dynamics of convergence under the above parameter values is showed in Figure 4.

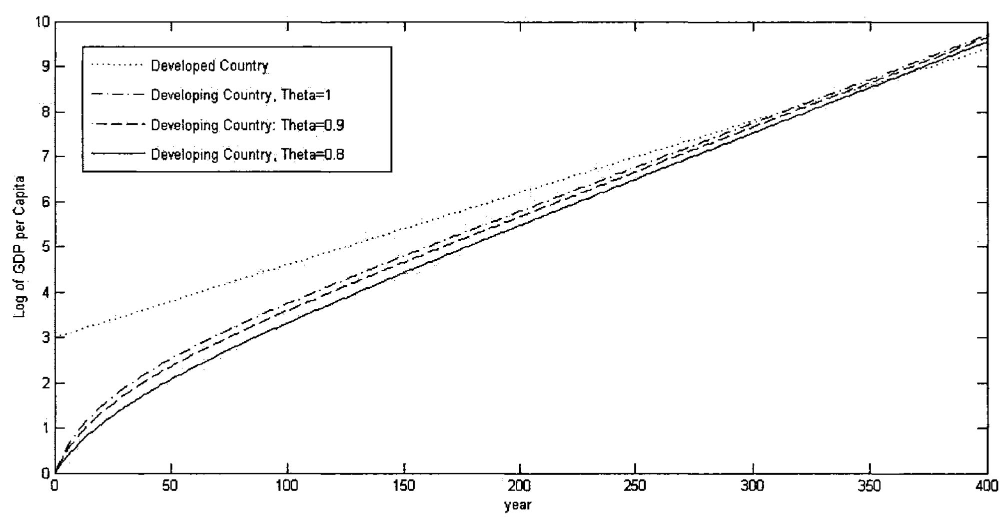

Figure 4. Convergence of the developing country to the developed country (in log of GDP per capita when θ= 0.8, 0.9, or 1). The overtaking part of this figure shall be ignored since the model ceases to apply after convergence.

The speed of convergence around 350 years may not seem so unreasonable if we consider the following:

(1) The initial gap of knowledge level (hence per capita income) was 20 times.

(2) In autarky, no convergence would ever happen.

(3) The target of convergence – the developed country is a moving target.

(4) Skilled return migration is the only catch-up mechanism considered in this model, whereas in reality there are other potentially more important catch-up mechanisms at work, such as foreign direct investment and international trade.

(5) In reality, some countries either never converge or drift farther away from the developed country.

One can appreciate more the benefits from skilled return migration to know that the net benefit is positive from day one for all $\theta \geq 0.781$ (under our "unrealistic" assumption of migrants possibly staying zero time in the advanced country). This can be demonstrated by looking at:

$$\dot{A}_0\big|_{migration} = 0.083\theta - \frac{0.045}{\theta^3} + 0.1 > \dot{A}_0\big|_{autarky} = 0.09\theta \quad (\forall \theta \geq 0.781). \tag{1.41}$$

For example, if $\theta = 0.8$, then $\dot{A}_0\big|_{migration} = 0.0785 > \dot{A}_0\big|_{autarky} = 0.072$. (Note that the initial growth rates are higher before they settle into the stead- state growth rates of 0.02 and 0.016 under migration and autarky respectively.)

Cross-Country Empirical Evidence from the US and New Zealand

Although there is anecdotal evidence in support of the growth-enhancing effects of return skilled migration, we look for a cross-country dataset to test the contribution of return migration to economic growth empirically.

Skilled Return Migration from US

However, a formidable barrier is that there is no uniform system of statistics on the number and characteristics of international migration (Carrington and Detragiache, 1998). Emigration data are even worse than immigration data, as the latter is available from census but usually the former is only available through a residual technique. For example, Ahmed and Robinson (1994) calculated the expected foreign-born population in US in 1990 based on the number of foreign-born persons enumerated in the 1980 census, adjusted by life table survival rates. An estimate of emigrating during 1980-1990 was obtained by the difference between the counted foreign-born population in the 1990 census and the above-expected population. Following a similar strategy, Mulder et al. (2002) provided updated estimates of foreign-born emigrants during 1980-1990 for only 14 developing countries. Among these 14 developing countries, four are from Asia (India, Iran, Korea and Philippines),[9] six from Central America (Dominican Republic, El Salvador, Guatemala, Jamacia, Trinidad & Tobago), and four from South America

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[9] China and Taiwan were combined together and had to be dropped from this dataset.

(Argentina, Colombia, Ecuador and Peru). All African countries were grouped together and therefore dropped from this dataset since the number of migrants was very small compared with other countries.

However, since the total number of emigrants was inferred, no information about their educational attainment was available. I have to assume that emigrants have the same structure of educational attainment as immigrants to the US for the same country of origin. The ratios of skilled immigration in total immigration are taken from Carrington and Detragiache (1998) to estimate the number of skilled emigrants and the rate of skilled return migration. See Appendix A, Return Migration Data.

Macroeconomic data are relatively easy to get. Data of real per capital GDP in 1990 and 2000 were obtained from Penn World Table Mark 6.1, from which the annual growth rates during 1990-2000 were calculated. Average years of schooling in 1990 were taken from Barro and Lee (2001). See Appendix B, Macroeconomic Data.

I ran a standard cross section growth regression in the spirit of Barro (1991) and Sala-i-Martin (1997), with the log of per capita GDP 1990, the average years of schooling and the rate of return skilled migration as explanatory variables. The OLS estimation results are below. Regressing the growth rate during 1990-2000 on the rate of return migration in 1990 helps avoid the reverse causation from growth rate to rate of return migration. See Table 2.

Table 2

Regression of Growth on Skilled Return Migration from US

$$\underset{(0.099)}{\text{GRATE} = -0.0080} + \underset{(0.013)}{0.0015\,\text{LGDP}} + \underset{(0.004)}{0.0005\,\text{ED}} + \underset{(1.091)}{1.2187\,\text{MIG}}$$

$n = 14, K = 4, R^2 = 0.11$

Robust standard errors are in parentheses

Note: GRATE = annual per capita GDP growth rate during 1990-2000

LGDP = log of per capita GDP in 1990 in 1996 constant price

ED = average years of schooling in 1990

MIG = rate of return skilled migration in 1990

Because it is a small dataset and it is largely concentrated in Central and South America, the R^2 is quite low (only 0.11), and the coefficient on the log of per capita GDP in 1990 is insignificant and has a wrong sign (it is slightly positive, but it should be negative according to conditional convergence implied by neoclassical growth theory). The coefficient on average years of schooling has the right sign but is also statistically insignificant. The coefficient on the rate of return skilled migration has the right sign, but it is only statistically significant at the 14.5% level (one-tailed t test).

Despite the poor data quality and possible endogeneity (higher growth rate attracts more return migrants), the most surprising finding is that the rate of return skilled migration outperforms the two standard regressants in cross-country growth regressions – the initial levels of income and the education.

Skilled Return Migration from New Zealand

Since 2001, New Zealand has required migrants leaving New Zealand to fill out departure cards that include information about their nationalities and occupation and whether they were on temporary or permanent departure. Hence this provides a direct measure of skilled return migration. Unfortunately, being a small immigrant country, only nine developing countries are specified in this New Zealand dataset, and most of them are from the Asia-Pacific region. Also, since immigrants to New Zealand only constitute a small portion of worldwide immigration, there is a question of how well skilled return migration from New Zealand can proxy for skilled return migration from all advanced (e.g., OECD) countries.

I grouped three occupations to make an operational definition of "skilled migration": "administrators and managers," "professionals," and "technicians." Also, I generated the stock of immigrants by adding up all skilled immigrants to New Zealand from 1981-2000 and subtracting all emigrants from 1981-2000. Then I used the structure of skilled versus nonskilled immigration in 2001 to estimate the stock of skilled immigrants. Data are listed in Appendix C and Appendix D. The regression results are found in Table 3.

Table 3.

Regression of Growth on Skilled Return Migration from New Zealand

$$\text{GRATE} = 1.1762 - 0.0083\ \text{LGNI} - 0.0067\ \text{ED} + 0.5236\ \text{MIG}$$
$$(0.112) \quad (0.017) \quad (0.005) \quad (0.576)$$

$n = 9, K = 4, R^2 = 0.53$

Robust standard errors are in parentheses

Note: GRATE = annual per capita GNI growth rate during 2000-2005

LGNI = log of per capita GNI in 2000 in PPP 2000 dollar

ED = average years of schooling in 2000

MIG = rate of return skilled migration in 2001

Although it is still a small sample, the R^2 has improved to 0.53 compared with the US emigration data. Both the initial income level and average years of schooling are not significant, and their coefficients are virtually zero. The coefficient of the rate of return skilled migration has the right sign, but it is statistically significant at 16% (one-tailed t test). However, it is remarkable that again the rate of skilled return migration outperforms that of initial income level and schooling, which are usually quite robust explanatory variables in cross-country growth regressions. Obviously, we can't draw too many conclusions from these two small datasets. But at least these regression results are consistent with and supportive of our model's prediction of a growth-enhancing effect through skilled return migration of skilled labor. More data and empirical research are obviously needed.

Policy Implications

Clearly a central policy implication from this model is that a developing country can and should utilize return migration as an effective mechanism to catch up with developed countries. Developing countries should do all they can to attract oversea skilled nationals to return to their home countries, particularly to improve the business environment and government efficiency, such as infrastructure, tax incentives, ease of regulations, government transparency etc. Accordingly, efforts to stop brain drain is ineffective and may be counterproductive with "beneficial brain drain."

A few further remarks:

(1) Infrastructure: While it may be difficult to boost infrastructure throughout the whole country, it is much easier to do so in a special economic zone or industrial park. It is also easier to offer tax breaks and easy regulations within a special zone. Hence it is potentially doable for many developing countries, especially those with a coastline and ports.

(2) Government: Government has an important role to play besides improving its efficiency. For example, the Taiwanese government set up the Hsinchu Industrial Park and aggressively promoted the recruitment of overseas talents. Government can also play a crucial role in fostering a domestic venture capital industry (Saxenian, 2005).

(3) Policy implications for developed countries: The phenomenon of "brain circulation" is a win-win situation. While some foreign skilled workers return to their home countries permanently, many more may stay in the developed country. Even those who left may still maintain close business ties with the developed country in promoting trade and economic cooperation. Some people may divide their time between two countries and become "transnational astronauts" (who often fly in the air). Furthermore, a world that is less polarized is certainly more conducive to economic and political stability and peace.

Conclusion

Instead of restricting brain drain passively, developing countries can have a more constructive approach to encourage return migration through a friendly business environment. This is a win-win outcome for both the developing and the developed countries. Within a framework of R&D-based endogenous growth, this model predicts catch-up and eventual convergence under fairly general conditions. Brain circulation may become a strategy for developing countries to catch up with the advanced countries. However, the speed of convergence depends on government efficiency in providing physical and institutional infrastructure and financial incentives. Directions for future researches include finding better and more complete data of return migration and determining specifically which government policies can promote return migration of skilled labor.

CHAPTER II

THE LABOR SCARCITY PARADOX: A GROWTH THEORETIC APPROACH

Introduction

The rapid development of American industrialization in the nineteenth century and its finally surpassing Britain at the turn of that century have intrigued many scholars for decades. According to Maddison (2001), the US GDP per capita was only three quarters that of the UK in 1820. But by 1913, the US GDP per capita was about 8% higher than the UK's. Apparently, the US income level caught up with the UK around 1900 (see Figure 5 below).

In his original thesis, Rothbarth (1946) surmised that this was largely due to America's abundant land and hence scarce labor (see Figure 6), which gave an incentive to install labor-saving equipment. Rothbarth proposed that in any country where land is available in large quantities, labor is likely to be expensive because the income of the industrial worker must be sufficiently high to present an attractive alternative to his cultivating the land. Thus the high productivity of labor in American industry at the beginning of this century can be explained by the fact that industry had to install labor-saving equipment. This hypothesis was further expanded and formalized by H. J. Habakkuk (1962), which established the conventional argument that America used more machinery[10] because of labor scarcity.

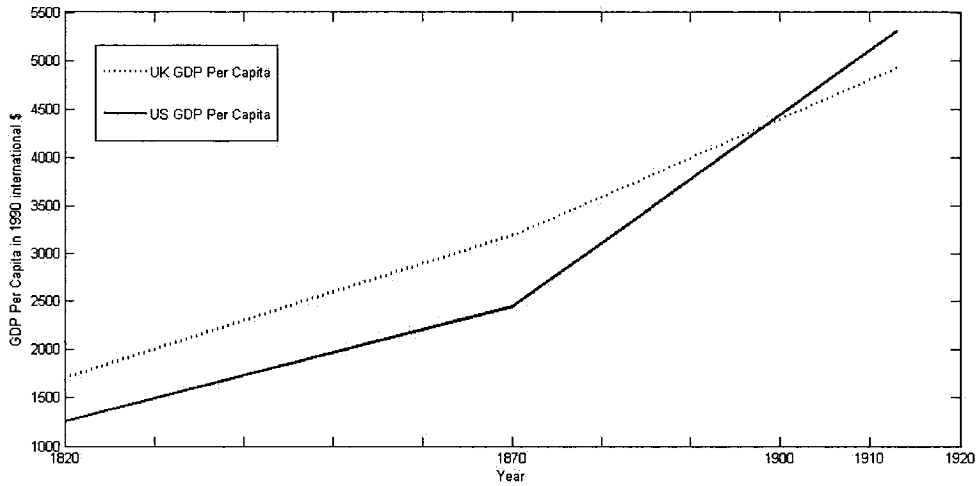

Figure 5. The US and UK GDP per capita in 1820, 1870 and 1913 (in 1990 international $). Data source: Maddison (2001), p.185, Table A1-c.

[10] It has also been proposed that America used "better machines" instead of "more machines" (Habakkuk, 1962). But "there were no American restrictions of the export of technology at the time. If the American System were truly better, then the British should have adopted it....Since they did not adopt American technology, this would seem to be proof that the 'better machines' argument is false" (Atack and Passell, 1994).

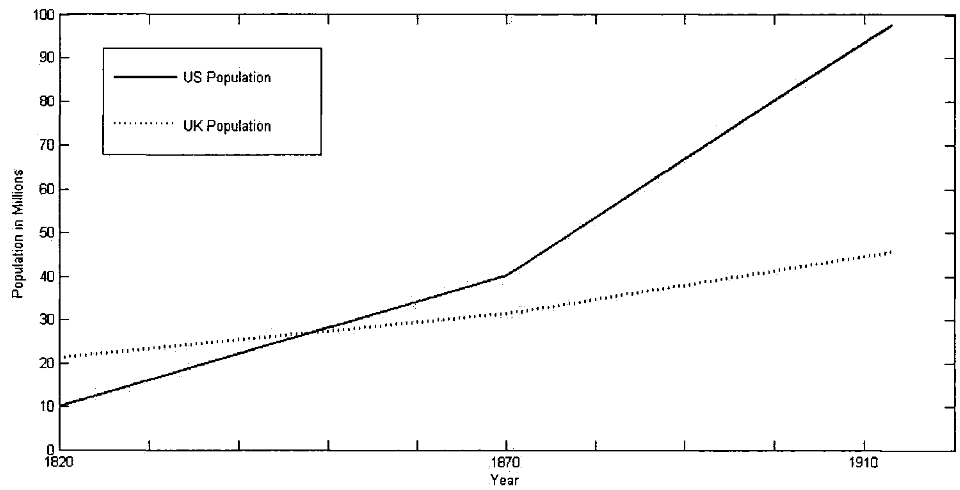

Figure 6. The US and UK populations in 1820, 1870 and 1913.
Data source: Maddison (2001), p.185, Table A1-a.

This hypothesis was seriously challenged by Peter Temin (1966), where he for the first time introduced a formal model into the discussion. In his two-sector (agriculture and manufacturing), three-factor (capital, labor, and land) model, labor scarcity necessarily implies capital abundance; in other words, higher wages must be accompanied by lower interest rates. Although real wages in America were estimated to be about 30% higher than in Britain (Rosenberg, 1967; Adams, 1970; James and Skinner 1985), the real interest rates in the United States were also consistently higher than in Britain during most of the 19th century (see Figure 7). Therefore, Temin was led to a startling conclusion that America was actually labor abundant.

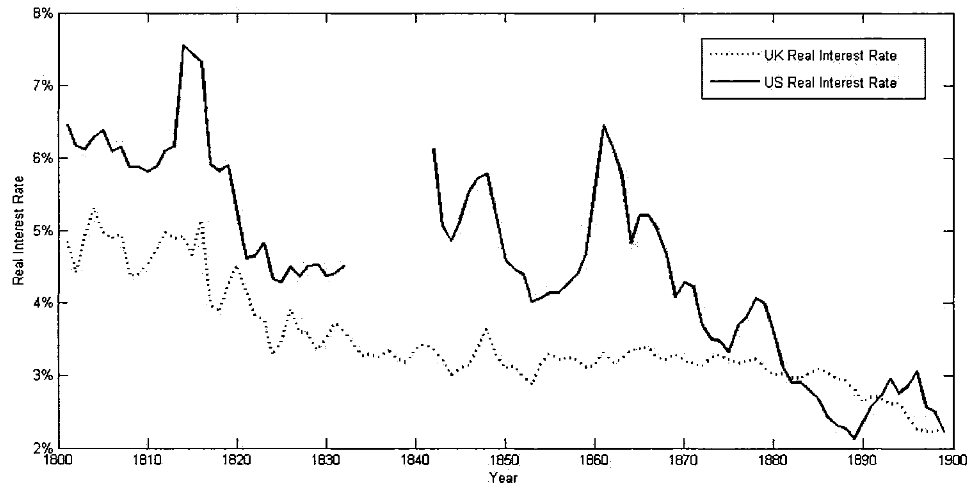

Figure 7. The US and UK real interest rates during 1801-1899. Source: Nominal interest rates are from Homer and Sylla (2005). Prices are from Historical Statistics of the United States (1975) and British Historical Statistics (1988).

However, Fogel (1967) showed Temin's specification to be unsatisfactory for failing to take into account the linkage between agricultural and manufacturing sectors. At the heart of Temin's model were the assumptions that agricultural output was a function of labor and land only while manufacturing output was a function of labor and capital only. Fogel (1967) pointed out that "firms employed in the processing of agricultural commodities account for more than 50 percent of the value added by the manufacturing sector in 1860" (p. 301). In this way, manufacturing output uses agricultural output as an input, and therefore uses land as an input indirectly. Fogel (1967) showed that Temin's argument would not go through under this modified model specification.

Summers and Clarke (1980) broadened the discussion to include international trade and capital flows. They showed that if factor supply was given, the relationship between labor scarcity and capital intensity could not be established. They turned their attention to *variable* factor supply -- capital inflow from abroad and long-term savings behavior. They agreed that international trade between America and Europe was minimal at that time, which meant that America did not import much physical capital, just liquid capital, the effects of which seemed only to increase America's money supply instead of the supply of capital goods. So the controversy still remained.

James and Skinner (1985) mounted an ambitious effort to resolve this paradox once and for all. Using 1849 US census data, they constructed a three-sector (agriculture, skilled manufacture, and unskilled manufacture), four-factor (capital, land, skilled labor, and unskilled labor) general equilibrium model to explain the following three empirical regularities for the antebellum period: "1) the United States was relatively capital intensive only in a limited number of manufacturing industries; 2) both the nominal and the real wage rates were higher in the United States than in Britain; and 3) both the nominal and the real costs of capital were higher in the United States than in Britain" (p. 517). The key point of their model is that while capital and natural resources are complementary in the skilled manufacturing sector, this relationship is not present in the unskilled manufacturing sector. Therefore, while the US skilled manufacturing sector was more capital intensive than in the UK, the manufacturing sector overall (dominated by unskilled manufacturing in the US at the time) was still less capital intensive than the UK. As a result, the US had both a higher real wage and a higher real interest rate around 1850.

However, despite its complexity and the careful general equilibrium simulation, James and Skinner's model was nevertheless static (i.e., it only models the US and UK economies around 1850, but not over time) and therefore missed the broad picture of American industrialization *process* and comparative American and British performance in the nineteenth century, which was the original focus of the Rothbarth-Habakkuk thesis. Their reliance on "skilled labor" to explain the labor scarcity paradox is also somewhat unsatisfactory, as "skilled labor" is usually endogenous in the long run but was treated as given in James and Skinner (1985).

This paper therefore focuses on the dynamics of US and UK economies in the nineteenth century as a complement to the detailed yet static study of James and Skinner (1985). We first review the central role of natural resource abundance in American industrialization. Based on this premise, we show that a calibrated Solow model augmented by natural resources offers a straightforward explanation of all empirical regularities of "labor scarcity" listed above while accounting for the dynamic process of America overtaking Britain.

The Central Role of Natural Resources in American Industrialization

Although Temin's (1966) original specification was not satisfactory, it nevertheless serves to show that the labor scarcity paradox (i.e., higher US real wage *and* higher US real interest rate) can't be reconciled within a two-factor framework. A natural choice is the introduction of natural resources as the important third factor. Essentially, both capital and labor were scarce in the US during the 19th century, and the abundant factor was natural resources.

America's abundant natural resources and their central role in the American industrialization process have been very well documented and emphasized by leading economic historians and theorists, for example, Ames and Rosenberg (1968), Christensen (1981), Wright (1990) and Romer (1996), among others. Before we proceed, we shall note that the word "industrialization" may not be very precise, since it also happened in agriculture. Maybe "mechanization" would be more appropriate under certain circumstances.

America's abundant resources included land, forest, raw materials, minerals and cheap energy, among others. For example, Christensen (1981) showed that while it only took 2.9 labor-weeks to purchase one acre land in the US in 1850, it would take 60.6 labor-weeks in Britain. Christensen (1981) further notes, "The abundance of natural capital – the climate, the fertility of the soil, the availability of water and timber, and the terrain – directly and indirectly facilitated the formation of farm capital" (p. 312). As a result, the total cost of farm-making (including breaking sod, fencing, barns, equipment, livestock, seeds, and the first-year maintenance) in America around 1850 was only about half of that of Britain. Therefore, American farms were typically larger, which "favored the more extensive use of horses and machinery." This created a large market for agricultural machines and equipment, such as "new cast-iron and steel plows, disks, harrows, cultivators, drills, planters, reapers and mowers" (p. 317).

Turning to the manufacturing sector, Christensen (1981) observed that America's "availability of low-cost energy presented a strong incentive for the adoption of power-intensive machine technologies" (p. 323). For example, in America water power was only "half as expensive as British (or American steam)" (p. 322) and "in the early decades of the 19th century, industrial power in America came almost entirely from water. By 1840, water still supplied nearly 90% of industrial power requirements" (p. 323). The resource-intensive nature of American technology in the 19th century was vividly demonstrated in different designs of steam engines in America versus Britain. While Britain relied mostly on low-pressure Boulton and Watt engines with "higher initial cost, greater complexity of operation, and better fuel consumption" (p. 324), the American steam technology was based almost exclusively on high-pressure engines, which were considerably lower in initial cost, easier to maintain and repair, but higher in fuel consumption.

The abundance of American "water" not only helped generate power, it also provided a much cheaper form of transportation through a vast system of natural internal waterways. Largely because of this:

> America led the world in the development and exploitation of the steamboat by the second quarter of the nineteenth century….Even the twelve-fold increase in tonnage between 1820 and 1860 drastically understates the growth in transport services provided by steamboat because of major increases in speed and in cargo capacity in relation to measured tonnage. (Rosenberg, 1972, p. 69)

In the same spirit, Ames and Rosenberg (1968) observed that "the woodworking machines which were popular in America and neglected in England were not only labor-saving but also wasteful of wood" (p. 831). The abundance of wood may have prompted the early invention and adoption of the lathe in the American gun-making industry, which greatly improved efficiency. As pointed out by Ames and Rosenberg (1968), "With Birmingham methods it required 75 men to produce 100 [gun] stocks per day. Using the early (1818) version of the Blanchard lathe, 17 men could produce 100 stocks per day" (p. 832).

In the area of metallurgy, America's resource abundance was also critical. After the "hot blast" technique was developed in England in 1828, it was quickly introduced to America in 1834 because "it permitted the exploitation of a resource [anthracite coal] which was highly abundant and readily accessible to America's main population centers" (Rosenberg, 1972, p. 81). In the 1890s, the "open hearth process" grew rapidly in America:

> Although it produced a superior steel as compared to the Bessemer process, the overwhelming advantage of the basic open hearth process was its ability to utilize a wide spectrum of the abundant phosphoric ores of the United States which could not be utilized by the Bessemer process. (Rosenberg, 1972, pp. 81-83)

In summary, abundance of natural resources played a central role in the American mechanization and industrialization process. A salient characteristic of American technology in the nineteenth century was its resource intensiveness and energy intensiveness. As characterized by Rosenberg (1977):

> Much of what distinguished the American experience was attributable to the fact that, when she commenced her industrialization in the first half of the nineteenth century, she did so with the pool of British experience upon which to draw, but also from a distinctively more favorable resource position. (p. 21)

Next, we turn to a parsimonious Solow growth model augmented by natural resources to account for this unique American industrialization process.

The Solow Model Augmented by Natural Resources

Motivated by the importance of natural resources in American industrialization and the need to account for the "labor scarcity paradox," we follow Solow (1999) to set up a three-factor Cobb-Douglas (1928) production function in capital, labor and natural resources for both the US and the UK. We assume that both countries share the same production parameter values of α and β. Because there was minimal restriction on technology transfer between America and Britain during most part of the nineteenth century (Habakkuk, 1962, pp. 96-97), it seems reasonable to assume the same production parameters, although the rates of technical change are allowed to differ due to the lag in technological diffusion across the Atlantic Ocean. This serves as a benchmark case, for which we later examine how well our model matches the data. It is assumed that the production function is:

$$Y = K^{\alpha}(AL)^{\beta} R^{1-\alpha-\beta} \ . \tag{2.1}$$

Country subscripts are suppressed at this point. A critical assumption is the presence of natural resources, R, which are assumed to be renewable and inexhaustible, i.e., a fixed constant. We further assume that natural resources are immobile between the US and the UK. This is plausible for the nineteenth century when the cost of transportation was high and the scale of international trade in natural resources was small.

As in the standard Solow model, the technology level A and the labor force L grow at constant rates of g and n respectively, and the capital stock K depreciates at the constant rate of δ. The saving rate is fixed at s. α, β and $1-\alpha-\beta$ are all between 0 and 1 and represent the income shares of capital, labor and natural resources respectively. To my knowledge, this formulation of natural resources in a neoclassical growth has not been taken very seriously yet in the literature. So this paper amounts to one of the first attempts to make it fully "operational" and test its validity through a particular application.

The dynamics of capital stock K are given by the following differential equation:

$$\dot{K} = sY - \delta K = sK^{\alpha}(AL)^{\beta} R^{1-\alpha-\beta} - \delta K . \tag{2.2}$$

In the standard Solow model, the trick to simplify the solution is to normalize the capital stock K by the efficient labor AL. Under the present setting, it turns out that the proper scaling is given by $(AL)^{\frac{\beta}{1-\alpha}}$, which reduces to the usual efficiency unit of AL when $\alpha + \beta = 1$. Effective capital and effective output are defined respectively by:

$$k = \frac{K}{(AL)^{\frac{\beta}{1-\alpha}}} , \tag{2.3}$$

$$y = \frac{Y}{(AL)^{\frac{\beta}{1-\alpha}}} . \tag{2.4}$$

Dividing both sides of the original production function by the efficiency unit $(AL)^{\frac{\beta}{1-\alpha}}$, we can rewrite it in the intensive form:

$$y = k^{\alpha} R^{1-\alpha-\beta} . \tag{2.5}$$

By definition, $K = k(AL)^{\frac{\beta}{1-\alpha}}$. Differentiate it logarithmically with respect to time to get:

$$\frac{\dot{K}}{K} = \frac{\dot{k}}{k} + \frac{\beta}{1-\alpha}\left(\frac{\dot{A}}{A} + \frac{\dot{L}}{L}\right) = \frac{\dot{k}}{k} + \frac{\beta}{1-\alpha}(n+g). \tag{2.6}$$

On the other hand, divide both sides of equation (2.2) by *K*, yielding:

$$\frac{\dot{K}}{K} = sK^{\alpha-1}(AL)^{\beta} R^{1-\alpha-\phi} - \delta = sk^{\alpha-1}R^{1-\alpha-\beta} - \delta . \tag{2.7}$$

Equating equations (2.6) and (2.7) yields:

$$\dot{k} = sk^{\alpha}R^{1-\alpha-\beta} - \left[\frac{\beta}{1-\alpha}(n+g)+\delta\right]k . \tag{2.8}$$

This is the fundamental equation governing the dynamics of the effective capital stock. Because the production function is Cobb-Douglas (1928), the normal assumptions of positive and diminishing returns and Inada conditions are automatically satisfied. This assures that no matter where the economy was initially (except the trivial and impossible case of $k_0 = 0$), it converges monotonically to a unique steady-state level of k^*, satisfying $\dot{k} = 0$:

$$k^* = \left(\frac{sR^{1-\alpha-\beta}}{\frac{\beta(n+g)}{1-\alpha}+\delta}\right)^{\frac{1}{1-\alpha}} . \tag{2.9}$$

Obviously, a higher level of natural resources *R* would raise the steady-state value of k^*. If we just blindly assume that all parameter values between US and Britain were the same except natural resources *R*, then ultimately the US economy would converge to a higher level of k^* than Britain. In reality, both the saving rate and labor force growth rate were higher in the US. As will be shown later, the end result was a much higher steady-state value of US capital stock per efficiency unit. Of course, the initial US level of capital k was much lower than Britain's, as it would be costly for new immigrants to bring too much capital stock with them to the New World. Most capital stock would have to be built up indigenously. One of the stylized facts emphasized by James and Skinner (1985) was that, overall, the US was still less capital intensive than the UK around 1850. According to Maddison (1982, Table 3.5, p. 54), the US capital stock per worker was about 83.5% that of the US in 1870.

Assuming that factors are paid their marginal products, then the real interest rate and the real wage are given by:

$$r + \delta = \frac{\partial Y}{\partial K} = \alpha k^{\alpha-1} R^{1-\alpha-\beta} \ , \tag{2.10}$$

$$w = \frac{\partial Y}{\partial L} = \beta A k^{\alpha} \left(\frac{R}{(AL)^{\frac{1}{1-\alpha}}} \right)^{1-\alpha-\beta} \ . \tag{2.11}$$

From (2.10), it is clear that before converging to the steady state, America's real interest rate would be higher than Britain's for two reasons. A usual reason was America's lower effective capital stock. Another reason was America's abundant natural resources, which raised capital's marginal efficiency. From (2.11), we see that despite the lower initial US capital stock, the real wage in the US was boosted by abundant natural resources, and it was possible for the US to have both a higher real wage *and* a higher real interest rate than Britain.

Calibration of the US and UK Economies in 1870

Production Parameters

Due to the paucity of historical data, I cannot estimate production function parameters α and β by standard econometric methods.[11] So we have to calibrate these parameters from income shares. Britain's labor income share had been quite stable. It was 0.63 in 1843, 0.625 in 1913, and again 0.625 in 1938. On the other hand, labor's income share in America had been declining from 0.80 in 1850 to 0.74 in 1910 then to 0.665 in 1938 (see Table 4). Habakkuk (1962) argued that "the fall is almost certainly to be explained by the decline in the number of self-employed persons as the result of the relative increase of industry..." (p. 36). If this were true, then the primary reason for America's high labor income share in 1850 was that it included returns from natural resources (such as land) owned mostly by self-employed individuals.[12]

[11] I tried running regressions using data from Maddison (1982) for Great Britain, but the parameter estimates don't make much sense with $\alpha = 0.66$ and $\beta = 1.2$. One reason is that the sample size is too small (every ten years from 1820 to 1913).
[12] In 1870, 50% of the total employment was in the agricultural sector in America while the British counterpart was only 22.7%. This gap would have been larger in 1850. Source: Maddison (1982), Table C5, p. 205.

Table 4

Labor's Income Shares in the US and the UK

Country/Year	1843	1850	1910	1913	1938
US	-	0.80	0.74	-	0.665
UK	0.63	-	-	0.625	0.625

Data source: Habakkuk (1962), p. 111.

If this were the case, then the difference of labor's income shares between America and Britain may proxy the income share for natural resources around 1850, i.e., $1-\alpha-\beta \approx$ 0.80 – 0.63 = 0.17. The remaining 0.2 (i.e., 1 – 0.8) is capital's income share. Therefore, as a baseline case, we assume the production parameters to be uniform across the US and Britain, with capital share $\alpha = 0.2$, labor share $\beta = 0.63$, and resource share $1 - \alpha - \beta = 0.17$.

Capital Stock, Labor Force, Population and Output

James and Skinner's (1985, p. 527) estimates of total capital stocks for the US and Britain in 1849 and 1851 respectively were somewhat problematic since they used current par exchange rates. To use PPP exchange rates, I start with Maddison's (1982,

Table 3.5, p. 54) estimates of the US and British capital stock per worker in 1870, which were $5,066 and $6,068 respectively.

The US and British labor forces are estimated to be 12.24 million and 13.95 million in 1870 respectively, and the labor force growth rates were 2.72% for the US during 1869-1909 and 0.89% for the UK during 1861-1911 (Broadberry and Irwin, 2006). Therefore, the estimated US and Britain total capital stocks in 1870 were $62,002.14 million and $84,654.15 million respectively.

The US and British population were estimated to be 40.241 million and 45.649 million in 1870 respectively (Maddison, 2001), which implies a lower labor force participation rate in the US (30.4%) than in the UK (44.4%).[13] But the US population grew at a faster rate of 2.08% compared with the UK's population growth rate of 0.87% during 1870-1913.

Per capita output data were also taken from Maddison (2001), which were $2,445 and $3,191 in 1870 for the US and the UK respectively in 1990 international dollars. The growth rates of per capita output during 1870-1913 were 3.94% and 1.90% for the US and the UK respectively.

[13] The explanation of why the US labor participation rate was much lower than the UK's is beyond the scope of this paper. It is taken as a given fact.

The Implied Values of Natural Resource Stocks

With the above estimates of α, β, capital stock, labor and output, it is straightforward to compute the stock of natural resources for the US and the UK using the production function (2.1) after normalizing the technology level A in 1870 to unity. As a benchmark case, we assume that the technology levels in the US and the UK were the same in the year 1870. This approximation may be reasonable since there was minimal restriction on technology transfer between America and Britain during most of the nineteenth century (Habakkuk, 1962, pp. 96-97), and the US inventive activities didn't speed up until the end of the nineteenth century. These assumptions imply that $R_{US} = 5.02 \times 10^{25}$ and $R_{UK} = 2.38 \times 10^{25}$.

Note that the absolute values of the natural resource stock do not mean too much, since I normalize the technology level in 1870 to unity. But it does imply that the US stock of natural resources is about 2.11 times that of UK, so that $\frac{R_{US}}{R_{UK}} = 2.11$.

The Implied Values of Interest Rates and Wage Rates

With this estimate of the resource ratio of the US to the UK, we can determine the implied ratios of real interest rates and real wage rates between the US and the UK from equations (2.10) and (2.11). Thus, $\frac{r_{US}}{r_{UK}} = 1.43$ and $\frac{w_{US}}{w_{UK}} = 1.12$.

The actual average real interest rates for the US and Britain during 1865-1874 were 4.47% and 3.26% respectively,[14] implying an interest rate ratio of 1.37, which is not far from the above figure of 1.43.

The implied ratio of real wages appears to be too low, with various estimates in the literature ranging from 1.25-1.52 (James and Skinner, 1985, pp. 537), but it is still broadly consistent. Due to the difficulty of measuring real wages, it could be that those historical estimates were overestimated.

In short, this model reconciles very well with the "labor scarcity paradox," i.e., the coexistent higher US real interest rate and real wage compared with the UK.

The Rate of Technical Change

We use a growth accounting procedure to estimate the average rate of technical change for the US and the UK. The average growth rates of the US and the UK capital stocks

[14] Data are from the same source as Figure 7.

are estimated at 4.7% and 1.62% respectively during 1870-1913 (Maddison, 1982, Tables D12 and D13, pp. 231-232). Production function (2.1) implies that the rate of technical change is given by,

$$\frac{\dot{A}}{A} = \frac{1}{\beta}\left(\frac{\dot{Y}}{Y} - \alpha\frac{\dot{K}}{K} - \beta\frac{\dot{L}}{L}\right). \tag{2.12}$$

This formula implies the following average rates of technical change during 1870-1913: $g_{US} = 1.935\%$ and $g_{UK} = 1.772\%$.

Saving Rates and Depreciation Rates

The US average saving rate was considerably higher than the UK's. According to Maddison (1982, Table 2.3, p. 40), the US saving rate was 13.8% during 1871-1910, compared with 6.875% for the UK during the same period.

We further assume that the depreciation rate was 5% for both countries, following the standard practice in macroeconomic calibration (e.g., Barro and Sala-i-Martin, 2004, Chapter 1). The result of the simulation in the next section is robust to different values of depreciation rates, e.g., 3% or 4%.

Numerical Simulation for the US and UK Economies During 1870 – 1913

The effective capital stocks for the US and the UK can be calculated as $k = \frac{K}{L^{\frac{\beta}{1-\alpha}}}$ after normalizing the technology level in 1870 to unity for both countries. Therefore, in 1870 the US and British effective capital stocks were k_{US_1870} = 162,483.87 and k_{UK_1870} = 200,112.23.

Again these absolute magnitudes do not mean very much since the technology level A was arbitrarily set to unity in 1870. However, it does show that in 1870, the US effective capital stock was about 81.2% that of the UK.

Was the American steady state level of the effective capital stock higher than the British? America's higher level of natural resources and higher saving rate both had positive effects. However, these effects were partly offset by America's higher population growth rate. From equation (2.9), the steady-state effective capital stock for the US and the UK were $k_{US}^{*} = 517{,}965.36$ and $k_{UK}^{*} = 237{,}379.68$.

Therefore, the US steady-state value of effective capital stock was about 2.18 times higher than the UK's.

With the above initial values of effective capital stocks in 1870, it is straightforward to solve the fundamental differential equation (2.8) numerically during 1870-1913. The simulation results are given in Figure 8.

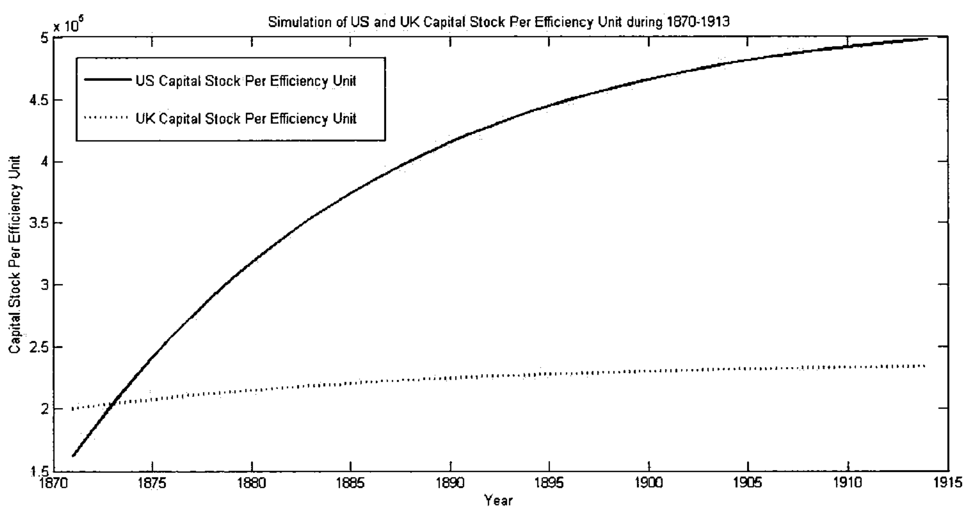

Figure 8. Simulation of the US and UK capital stocks per efficiency unit.

From the above simulations, it is clear that both the US and the UK capital stocks converged to their respective steady-state values. At first sight, it looks surprising that the "overtaking" happened around year 1873, which was before most economists' estimate the overtaking occurred, which most economists believe was around 1890. However, this was capital stock per efficiency unit. It is not capital stock per worker or GDP per capita.

Next, we look at the simulation of GDP per capita for the US and the UK during 1870-1913, which does correspond to the actual "overtaking" year pretty well (Figure 9).

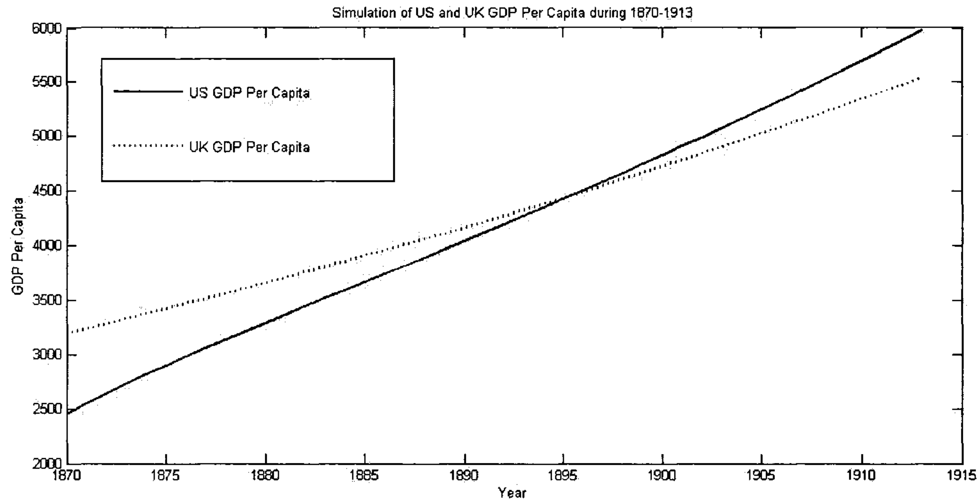

Figure 9. Simulation of the US and UK GDP per capita during 1870-1913.

The above simulations indicate that the US GDP per capita overtook the UK around 1895, which matches very well with the historical fact in Figure 5 at the beginning of this paper. However, the predicted values of GDP per capita in 1913 ($5,979.16 and $5,541.33 for the US and the UK respectively) were a bit higher than the historical statistics ($5,301 and $4,921 respectively) in Maddison (2001). The US and the UK GDP per capita were overpredicted 12.8% and 12.6% respectively over the span of 43 years from 1870-1913 (i.e., they were only overpredicted by about 0.3% per year). Overall, the fit of the model is pretty good, and it mimics the actual process of America catching up with Britain toward the end of the nineteenth century.

Conclusion

The neoclassical growth model is one of the most robust models in economics and has become a workhorse in macroeconomics for decades. This paper again demonstrates its power in organizing our understanding of the comparative US-UK economic performance in the nineteenth century. The apparently complex interactions among the three productive factors of capital, labor and natural resources in America, known as the "labor scarcity paradox," become transparent through a Solow model augmented by natural resources. Calibration results match all empirical regularities of the American and British economies around 1850. Numerical simulations mimic the dynamic catching up process pretty well. It is hard to imagine how we could gain this clarity of understanding without a growth framework.

Of course, this model would not hold in the twentieth century with increasing international trade and factor mobility. The assumption of resource immobility lost its validity. Countries with little resources such as Japan have achieved great economic growth. However, overall this Solow model augmented by natural resources does a pretty good job in describing the comparative growth experience of the US and the UK in the nineteenth century, and it is a success of the neoclassical growth model.

CHAPTER III

THE NEEDHAM PUZZLE RECONSIDERED: THE ROLE OF LEGAL INSTITUTIONS

Introduction

In the late 1930s, Joseph Needham raised his now famous puzzle: Why, with all of its great technological achievements (Needham 1954, Temple 1986), didn't the Industrial Revolution and the inception of modern science take place in China? According to Needham (1954), Chinese "technological discoveries and inventions were often far in advance of contemporary Europe, especially up to the 15th century" (p. 6). Francis Bacon (2000) famously claimed that the three major Chinese inventions - paper, compass and gunpowder - had reshaped the world. This contrasts sharply with China's stagnation in modern times for centuries. China's ancient technological prowess was also reflected in economic historians' estimates of per capita income. According to

Maddison (2001), in year 1,000 China's per capita GDP was among the highest in the world, i.e., $450 compared with $400 for Western Europe (both in 1990 international dollars) (p. 264, Table B-21; see Figure 10).

As reflected by Mokyr (1990), "The greatest enigma in the history of technology is the failure of China to sustain its technological supremacy" (p. 209). Obviously, a better understanding of the Needham puzzle has far-reaching implications for not only China, but also the entire developing world, especially where the Industrial Revolution is yet to fully unfold.

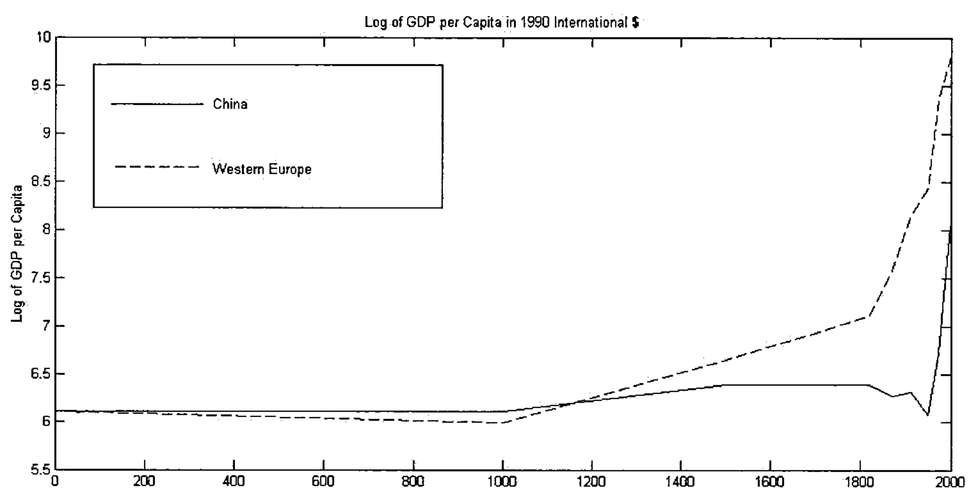

Figure 10. Log of GDP per capita for China and Western Europe during A.D. 0-1998 (in 1990 International $). Source: Maddison (2001), p. 264, Table B-21.

Many scholars have attempted to answer this intriguing question. A host of factors have been proposed, ranging from cultural, philosophical, religious, psychological, and economic factors as candidates. It may have even become a pasttime for China scholars.

For example, Wang (2002) compiled an 886-page selection of essays in Chinese aiming at resolving this puzzle from almost all possible aspects. But noneconomic explanations usually cannot stand under close scrutiny (Mokyr 1990), since noneconomic variables are usually slow changing and can't be easily reconciled with China's dramatic change in fortune. This paper focuses on economic explanations. Existing economic answers can be roughly classified into two categories: demand failure theories (Elvin, 1973; Tang, 1979; Chao, 1986) or supply failure theories (Baumol 1990; Murphy et al., 1991, 1993; Lin, 1995).

The demand failure hypothesis – also called "the high level equilibrium trap" - maintains that China's unfavorable man-to-land ratio diminished (if not eliminated) her demand for new technology, since labor was so abundant and cheap in China. A high man-to-land ratio also meant that there wasn't enough surplus or saving for research. This line of approach was proven to be empirically unimportant by Lin (1995). Using historical data, Lin found little empirical correlation between China's man-to-land ratio (population divided by cultivated land) and the speed of technological progress.

Interestingly, Pomeranz (2000) seemed to revive this "resource endowment" hypothesis and maintained that Europe and China (especially the respective advanced areas, namely England and the Yangtze delta) were basically comparable before 1800 in population history, agriculture, handicraft industry, income and consumption. "The Great Divergence" happened only after 1800 largely because of the lucky availability of coal in England and other raw materials from the New World. However, neoclassical growth theory since Solow (1956) made it clear that capital formation alone is not enough to sustain long-run growth without continuous technical change.

Lin (1995) offered a supply-side explanation instead; i.e., the Industrial Revolution depended critically on the Scientific Revolution, which for many reasons did not happen in China. Another supply failure theory (Baumol, 1990; Murphy et al., 1991, 1993) proposed that China's civil service exams created too much rent-seeking opportunities, which drained Chinese geniuses from productive innovation into unproductive or even destructive rent-seeking activities.

A central finding of this paper is that supply-side hypotheses are not important in practice either. Even with enough potential demand and supply for new technology in premodern China, technological progress could still stagnate due to market failure and the lack of formal institutions defining the ownership of intellectual properties, such as patent protection. Since the influential work of North and Thomas (1973) and North (1981, 1990), institutions are increasingly viewed by many as the key to long-run economic performance. In an important empirical study, Acemoglu et al. (2001) used colonial settlement mortality variable as an instrument and found large effects of institutions on income per capita. Therefore, it is surprising that few scholars have linked China's institutional weakness to the resolution of the Needham puzzle. This paper attempts to fill this gap by focusing on a particular institution - patent protection - as a prominent example.

Of course, Industrial Revolution was a very complex phenomenon with many interrelated facets. In a broad sense, this paper is in agreement with Eric Jones's (2003) position that the strength of Europe lay in many factors going back for centuries. The exact dating of when Europe overtook China is not specifically relevant – Maddison (1998) put it in the fourteenth century while Pomeranz (2000) put it as late as 1800 - but the truly amazing thing about Europe was its ability to build a solid institutional foundation (culminating in patent laws, etc.) to support sustainable growth and innovation.

The rest of this paper is organized as follows. Section 2 reviews the Scientific Revolution hypothesis and presents theoretical and empirical evidence against it. Section 3 examines and dismisses the rent-seeking argument. Section 4 highlights the differences between ancient and modern modes of invention. Section 5 provides an inventor's choice model, through which the importance of patent protection is deduced. Section 6 presents cross-country statistical evidence of the impact of patent laws on invention rates. Section 7 asks whether James Watt could have been a Chinese and examines his life as a case study. Section 8 reflects on China's lack of legal tradition. Section 9 concludes.

How Important Was the Scientific Revolution?

Lin (1995) maintained that China was lucky in the premodern world because her sheer population size increased the chance of experience-based invention through trial-and-error (i.e., more people means more chances of trial-and-error leading to inventions) and became lackluster when invention became increasingly based on experiment-cum-science since the Industrial Revolution. From year 0 to 1600, China's population was roughly twice as big as all of Europe (including Western and Eastern Europe). See Figure 11.

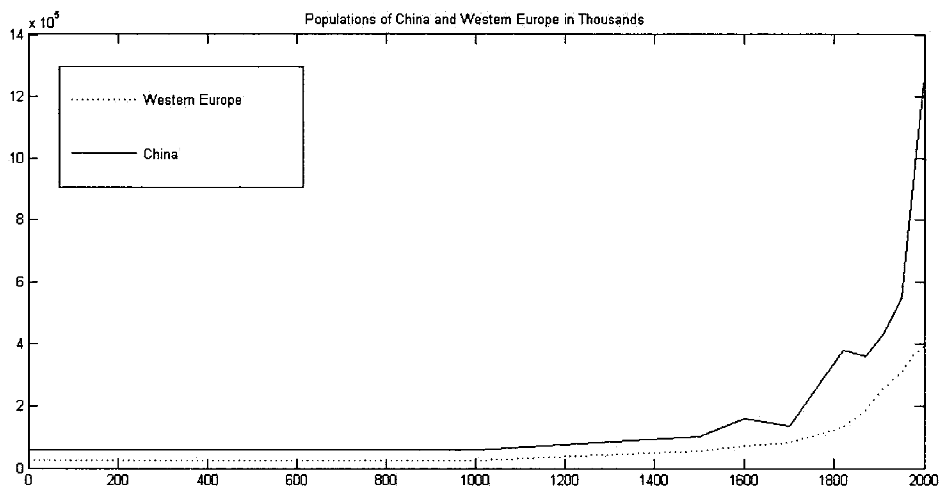

Figure 11. Populations of China and Western Europe during A.D. 0-1998 (in millions). Data source: Maddison (2001), p.241, Table B-10.

Kremer (1993) documented that the differential long-term economic performance of five regions on earth (Eurasia/Africa, the Americas, Australia, Tasmania, and the

Flinders Island) isolated from each other since the end of the last ice age around 10,000 B.C. closely matched up with their initial population ranks. Basically, more people mean more ideas can be created.

However, the second half of Lin's hypothesis is problematic. It is far from consensus that the Industrial Revolution depended historically on the development of science. According to Musson (1972), "At the beginning, the contribution of science to technology was sporadic; in fact whether or not science was a major contributing factor to the Industrial Revolution in the eighteenth century is still subject to debate" (p. 58). Polanyi (1962) put it bluntly, "Up to 1846 natural science had made no major contribution to technology. The Industrial Revolution has been achieved without scientific aid" (p. 182). Although science has played a significant role in technological progress since the mid-nineteenth century (Cameron, 1989), that was about a century later. As mused by Rosenberg and Birdzell (1986), "The West surpassed other societies in…science – by the time of Galileo, say, 1600….But the wealth of Western economics did not clearly draw ahead of the wealth of their predecessors and other economies for another hundred and fifty or two hundred years" (p. 254). Any attempt to give the Scientific Revolution a direct role in the Industrial Revolution would have to somehow explain away this awkward gap of one or two hundred years between the two.

In his study of British patent data during 1711-1850, Sullivan (1990) tested the role of science on invention. His idea was that if science was important during the Industrial Revolution, then the most relevant direct link:

> would have been from advances in chemical and mechanical science to chemical and mechanical invention. If this were significant, we should observe increasing shares of patenting for heavy chemical and machine inventions, but the patent data show only decreasing or constant shares. (p. 359)

Therefore, Sullivan (1990) concluded that "the patent data do not, however, reveal a pattern that suggests a large influence of scientific advance on invention" (p. 359).

A direct test of the Scientific Revolution hypothesis, however, is to examine how much stock of scientific knowledge those major British inventors during the Industrial Revolution had acquired. If most of them did not have significant scientific training, this would weaken the Scientific Revolution hypothesis. Twelve major British inventors are identified in the article "Industrial Revolution" in Encyclopedia Americana (2002) by Hugh G. Cleland. (American inventor Eli Whitney was also mentioned, but omitted.) Among them, six were in the textile industry, three in the steam engine industry, two in the iron industry and two in the steam transportation industry (see Table 5). Out of these 12 major British inventors, only two of them received college educations (a ratio of $\frac{1}{6}$), and one of them majored in religion. Although college education was still rare in Britain around that time, this does cast doubt on the importance of science on the Industrial Revolution. This finding is consistent with Rosenberg and Birdzell's (1986) assertion that "until about 1875, or even later, the technology used in the economies of the West was mostly traceable to individuals who were not scientists, and who often had little scientific training" (p. 244). The bottom line is that if the Scientific Revolution were crucial for the Industrial

Revolution, then we should be able to name specific scientific knowledge that was responsible or indispensable for major inventions during the Industrial Revolution. But to my best knowledge, no one has been able to name it.

Table 5

Education of British Inventors during the Industrial Revolution

Inventor	Years Lived	Industry	College Education	Patents Acquired
Richard Arkwright	1732-1792	Textile	No	Yes
Edmund Cartwright	1743-1823	Textile	Yes (in religion)	Yes
Samuel Crompton	1753-1827	Textile	No	No
James Hargreaves	1702?-1778	Textile	No	Yes
Lewis Paul	? - 1759	Textile	Little is known	Yes
Thomas Newcomen	1663 - 1729	Steam Engine	No[15]	Yes
Thomas Savery	1650 - 1715	Steam Engine	Yes	Yes
James Watt	1736 - 1819	Steam Engine	No	Yes
Henry Cort	1740 - 1800	Iron	No	Yes
John Wilkinson	1728 - 1808	Iron	No	Yes[16]
John McAdam	1756 - 1836	Steam Transportation	No?	No?
George Stephen	1781 - 1848	Steam Transportation	No	?

Sources: *Encyclopedia Americana* (2002) and *Encyclopedia Britannica* (1995).

[15] http://es.rice.edu/ES/humsoc/Galileo/Catalog/Files/newcomen.html

[16] http://www.wrexham.gov.uk/english/leisure_tourism/culture_heritage/JohnWilkinson.htm

Perhaps the strongest case for the importance of Scientific Revolution was made by Mokyr (2002). While admitting that "it would be a grave error to suppose that the Industrial Revolution in its early stages was driven by a sudden deepening of the scientific foundations of technology" (p. 32).

Mokyr (2002) maintained that the development of science was crucial in preventing the Industrial Revolution from fizzling out like previous technological spurts had done in history. In his view, the key point of the Industrial Revolution wasn't that it happened, but rather that it was continued by the Second and Third Industrial Revolutions.

However, there are several difficulties associated with this view. First, although it helps explain "why Europe," it has nothing to say about "why Britain, not France," because it is not tenable to argue that Britain was more advanced in scientific development than France. Second, the reverse of Mokyr's thesis is also true, if not more so; i.e., the Scientific Revolution was able to continue without petering out like previous spurts (e.g., the great scientific achievements of the Greek and Islamic civilizations) because of the sustained Industrial Revolution (running on its own for at least one hundred years), which created the demand, motivation, and means to deepen scientific investigation into an industry from a hobby of the privileged few driven by curiosity (Fox and Guagnini, 1999).

Even if we accept Mokyr's thesis wholesale, then there would be nothing to prevent China from generating the First Industrial Revolution and sustaining it for one to two hundred years, and the great divergence between Europe and China wouldn't begin until Europe embarked on the Second Industrial Revolution thanks to the deepening of science. But a China transformed by the First Industrial Revolution would have all the motivation to borrow from this reservoir of European knowledge in no time – in this case, there wouldn't be any "great divergence" after all.

In summary, it is a huge oversimplification to blame science for China's lack of Industrial Revolution, and it misses the main point.

Was Rent Seeking Important?

Although Baumol (1990), Murphy et al. (1991, 1993) were not written to explain the Needham puzzle per se, they cited China as an example to support their rent-seeking theory. According to this theory, the Chinese civil exam system drained Chinese talents into ethics and poetry and away from inventive activities.

A critical assumption in this theory is that capable people are capable in all areas. According to this theory, when rent-seeking opportunities abound, a country's most talented leave productive arenas (such as invention or entrepreneurship) to engage in unproductive or destructive rent seeking (such as poet-officials in China, tax collectors or religious clerics in Western Europe). Therefore, only people of secondary caliber are left in the productive arena. This slows down the technological progress since secondary people can only make secondary innovations.

However, people who are good at literature and socializing are not necessarily good at mechanics and engineering. If the chances of inheriting good engineering genes and good literature genes are both 10% and independent (or the correlation is sufficiently weak), then the probability of inheriting both genes is merely 1%. This explains why in reality truly Da Vinci-style versatile people are few and far between, and geniuses are often skewed and biased.

In any society, there will be a highest paying profession, be it officials, army officers or entrepreneurs. This doesn't necessarily harm inventive activities. The key issue is whether the reward from invention is enough to cover expenses and make a decent living. CEOs in America have generous paychecks. But it doesn't prevent American inventors from doing path-breaking research. Murphy et al. (1991) pointed out:

> In eighteenth century France, the best and the brightest also became rent seekers. The great chemist Lavoisier's main occupation was tax collecting, and Talleyrand was a bishop with a large tax income despite his prodigious entrepreneurial skills shown when he escaped to the United States after the French Revolution. (p. 505)

However, there were also tax collectors and bishops in contemporary Britain, and it is hard to determine whether France had more of them than Britain. One of the major

British inventors mentioned before, Edmund Cartwright, was the rector of a church as well. What distinguished France from Britain historically seems to be the absence of positive incentives rather than the presence of negative incentives.

In the case of ancient China, although the reward for becoming an official through the civil service exams was very high in the forms of official pay, rent-seeking opportunities (Huang, 1997) and social prestige, the likelihood of winning these exams was very low due to its tournament nature and China's huge population. The majority failed, and their failure became a recurring theme in Chinese literature. Because of fierce competition, it usually took more than 10 years of diligent study to prepare for the exams (often dubbed as "ten years of facing cold windows" in China). It is well known that an occupation that requires a longer period of training will have to be compensated more in order to equate the returns between different occupations (Mincer, 1958). Despite the remote chance of success and lengthy wait time, most Chinese intellectuals historically chose to pursue civil exams simply because there weren't any decent alternatives. The reward from inventions was very low because there was no patent protection to guarantee that they could recover the expenses and reap the benefits. Understandably, when the Chinese civil exam system was finally abolished in 1912, things did not improve immediately.

Premodern inventors were mostly not intellectuals. They were more likely artisans, smiths, or farmers who were familiar with the production processes. Historically, it is difficult to subscribe to the view that China has ever had a shortage of skillful and ingenious smiths and artisans among her large population. In premodern times, the demand for handicraft and repair work was more likely to be quite stable in an agrarian economy. Whether they did come forward to engage in inventive activities was a different consideration, to be explored in the next section.

Empirically, the rent-seeking hypothesis is also anachronistic. The civil exam system was instituted in China as early as the Sui dynasty (589-617), and China continued to make important inventions and lead the world technologically until before the Industrial Revolution (1760-1840). If the civil exam system had drained China's technological creativity, Chinese civilization should have flounder as early as the 6th century, when China was actually poising to enter a long and prosperous age.

The Modes of Invention: Then and Now

Lin (1995) proposed an apparently ingenious way to reconcile the Needham puzzle. According to this view, ancient inventions were based on "experience," which depends largely on the population size. A larger population means that there are more "trials and errors" and a higher chance of invention. On the other hand, modern inventions since the Industrial Revolution are based on "experiment-cum-science," which failed to happen in China.

However, the difference between "experience" and "experiment" is somewhat vague. Ancient inventors could and did do experiments. A better distinction is that ancient inventions were mostly the results of costless learning by doing while modern inventions are characterized by deliberate and costly R & D. Why did China invent the compass and gunpowder but couldn't use them more productively as compared with Europe? The initial discoveries might happen through happy serendipity during trial and error, but continuing improvement and perfection certainly required substantial R & D investment, which were not supported by Chinese institutions.

Following Lin (1995), we can think of the process of technological invention as a random draw through trial and error from a distribution of productivity. Technological progress occurs when a draw yields higher productivity than the current level. More people mean more draws and hence more technological progress. However, if this productivity distribution is fixed, then finding a higher level of productivity becomes increasingly difficult. According to Lin (1995), the Scientific Revolution shifted this distribution rightward, resulting in a spurt of new inventions. But we have shown in the previous section that the Scientific Revolution was unlikely to be historically responsible for such a shift. Instead, the increase in R & D spending was crucial. When a researcher is doing "trial and error," there are infinitely many different ways to do it with entirely different cost and benefit profiles. The method of experiment not only means that it can be repeated many times but more importantly in many different ways than the existing production process. After thousands of years exploring at the low end of R&D expenses, the potential of learning by doing gradually diminished and dried up.

The possibility of making epochal invention became very remote. On the other hand, the high end of R&D expenses is a still fertile land. It was a systematic and dramatic increase in R&D expenses that pushed the research frontier significantly outward.

A Simple Model of Inventor's Choice

In order to analyze what caused this systematic and dramatic increase in R & D expenses, a simple model of inventor's choice is used below. We do not claim much novelty of this model. It is static. But it provides a useful framework for exposition purposes. Assume that a potential inventor allocates his total fixed time ($\bar{L}$) between invention (L_1) and regular artisan work (L_2) to maximize income (*Y*):

$$\max_{\{K,L_1\}} \quad Y = p\left[EQ_1(K,H,L_1)+EQ_2\left(\bar{L}-L_1\right)\right]-(r+\delta)K+w\left(\bar{L}-L_1\right) \qquad (3.1)$$

$$\text{s.t.} \quad 0 \le K \le \bar{K} \quad \text{(liquidity constraint)}$$

$$0 \le L_1 \le \bar{L} \quad \text{(time constraint)},$$

where EQ_1 is the expected output of invention through R & D, which is a function of R & D capital *K*, the inventor's human capital *H* (assumed exogenous here), and the time devoted to inventive activities L_1. EQ_2 is the expected output of coincidental invention through learning by doing, which happens as a byproduct of his regular artisan work. Theoretically, the more time is devoted to regular artisan work, the more likely it is to experience learning by doing. Practically, the chance of a happy discovery is remote for an individual (although it may be significant at the aggregate level). It may take an artisan decades of repeating the same production process before landing on a truly inspiring idea. Therefore, we neglect this "learning by doing" term EQ_2 in this maximization problem. In any case, before the Industrial Revolution, the potential of learning by doing without significant R & D was almost exhausted.

The unit price of invention, *p*, is a hypothetical market price if the invention (say, patent) is to be sold in a market with perfect information. Under an ideal situation, the value of a patent is determined by the discounted sum of expected future profits accruing from manufacturing commercial products using this patent; *r* is the interest rate of capital financed, δ is the rate of depreciation, and *w* the wage of regular artisan or alternative work. The inventor takes all prices, his human capital stock *H*, and maximum available capital $\overline{K}$ as given. Assuming interior solutions, the first-order conditions are $\frac{\partial Q_1}{\partial K} = \frac{r+\delta}{p}$ and $\frac{\partial Q_1}{\partial L_1} = \frac{w}{p}$ respectively.

It is immediately clear that the lower the patent price is, the lower the optimal inventive capital and inventive labor are, and hence the lower the inventive output would be. Furthermore, if the patent price is zero, then all inventive inputs and output are zero. What determines a patent's price? It depends on its potential profitability (e.g., the size of its applicable market), how easy it can be imitated, and the effective protection of intellectual properties. If a new invention is very profitable but can be easily imitated without significant technical or legal costs, then imitation products will soon flood the market. In a perfectly competitive market with free entry, this new industry born out of the invention will quickly reach its industry-wide equilibrium, and each firm will earn zero profit. In this case, the price of an invention may be too small and potentially tending to zero. In this case, the original inventor will not be able to recoup his research expenses and will suffer losses. Of course, ex ante, he won't even embark on this adventure to begin with. This is a classic case where the private rate of return falls short of the social rate of return (North and Thomas, 1973).

In his path-breaking paper, "Endogenous Technological Change," Romer (1990) made this point crystal clear. The basic premise is that the inventor has to be a monopolist of his invention for at least a period of time in order to fully recover the R & D expenses and make a profit. Otherwise, the potential inventor would not engage in R&D in the first place. As pointed out by Romer, this same argument has been made many times before (Schumpeter, 1942; Arrow, 1962; Shell, 1966; Nordhaus, 1969; Wilson, 1975). To the extent that the large literature of new growth theory spawned by Romer (1990) is a useful guide in understanding long-run growth, the importance of patent protection follows inexorably as a precondition.

Of course, there are inventions that cannot be easily imitated, and a monopolistic position can be simply maintained through secrecy. CocaCola's secret recipe and

Windows Operating System's source code are two examples. However, many important inventions, especially those inventions during the Industrial Revolution of a mechanical nature, can be readily reverse engineered without much cost. After an ingenious inventor designed a new machine, other engineers could easily break it down to see how it works and make a clone. Therefore, in a society without patent protection, innovation may be strongly biased towards industries where secrecy may be enough protection, and inventions requiring patent protection may be delayed forever.

The price of a patent also depends crucially on the profitability of the firm using this patent. Firms' profitability in turn depends upon business law for guaranteed smooth business transaction and protection of personal property rights.

In her innovative empirical study of 15,000 innovations at the Crystal Palace World's Fair in 1851 and at the Centennial Exhibition in 1876, Moser (2005b) found that inventors in countries without patent laws (Denmark, Switzerland, and after 1869 the Netherlands) focused on a small set of industries where patents were less important (e.g., scientific instruments and food processing), whereas innovation in countries with patent laws appears to be much more diversified. The abolition of the Netherlands' patent laws in 1869 due to largely ideological reasons gave Moser (2005a) a chance to isolate the effect of an exogenous shock of patent laws on innovation. After the Netherlands abandoned patent laws in 1869, the country's innovation experienced a strong shift towards food processing, an industry where secrecy was important.

Furthermore, technological diffusion may be as important as inventing new techniques. Patent laws promote technological diffusion by adding new knowledge to the public domain as soon as they become available, while secrecy prevails without patent protection. Moser (2005a) found that innovations in industries with high patenting rates were geographically dispersed, whereas innovations in industries with low patenting rates were geographically concentrated. Without patenting, innovation clustered not only within counties but also within cities.

Another function of patent protection is to facilitate the transmission of new technology. To receive patent protection, it is necessary to reveal the new "formula" to the public, which becomes freely available after the patent expires. Without a patent law, many new inventions were often kept as business secrets for a long time, if not forever. This may be particularly so in China's history. Many high-quality products (including agricultural and handicraft products) were produced from a small local area or sometimes concentrated in just one city, indicating that state-of-the-art technology was difficult to diffuse throughout China.

In the long history of human civilization before the Industrial Revolution, invention happened at a very slow pace. Why did it suddenly accelerate and first in Britain? In fact, it was a quantum leap for a society without patent protection to jump into a society with patent protection. It is widely acknowledged that the first patent statute was enacted in Venice as early as 1474, and patents were granted even before that. But why didn't the Industrial Revolution happen in Venice first? Remember that the price of an invention also depends on the size of its applicable market. Venice was only a city state with a small population (likely between 100,000 – 150,000 in the fifteenth century), and Venice was more a commercial than an industrial center (Nard and Morriss, 2004). Since this patent law was only applied to a small market, its impacts on technological progress were limited.

Britain became the first country to adopt a patent law in 1623. The seed for large sustained innovation was planted. In a little more than one hundred years, it bloomed into a full-fledged Industrial Revolution. According to Table 5, almost all key inventions by major British inventors during the Industrial Revolution were patented. Historically, America adopted a patent law in 1790, followed by France in 1791, which was almost one and a half centuries later than Britain. There has been a heated debate among scholars about whether Britain had an ex ante higher probability of the Industrial Revolution than France (for example, Crafts 1977, 1995). However, from the perspective of patent protection as a crucial incentive, Britain's advantage was apparent and inevitable.

The Chinese patent system is one of the youngest in the world, unfortunately delayed by wars and failed reforms (Ganea et al., 2005). In 1898, a patent law was first enacted by the reform-oriented emperor Guangxu of the last Qing Dynasty. After Guangxu lost his own freedom, his reform was short-lived. The Nationalist government enacted a patent law for China in the turbulent year of 1944, which never entered into full force in mainland China (but was preserved in Taiwan). During 1950-1963, only four patents and six inventor certificates were granted in mainland China, and the system was abolished in 1963 altogether. The present patent law was finally enacted in 1984, although the preparations and training of patent staff started as early as 1979.

Certainly, with frequent media reports of rampant piracy in China, her patent system and enforcement are still widely considered inadequate. Nevertheless, Ganea et al. (2005) were amazed by "the high number of patent applications the Patent Office is capable of handling" (p. 3). La Croix and Konan (2002) concluded that although enforcement of intellectual property rights within China continues to be relatively weak, they are converging on those in the OECD nations. Furthermore, the role of patent protection in generating an indigenous Industrial Revolution versus assimilating advanced foreign technology can be quite different. A rigorous patent system may not always serve the best interest of a developing country, as it may negatively affect its borrowing of foreign technology (Chen and Puttitanun, 2005).

Besides the important issue of patent protection, it is worth pointing out that the availability of financial capital may also become a limiting factor, when optimal capital input is a corner solution and inventors have to rely on external financing. Therefore, a well-developed financial system and corporate governance are also crucial for an Industrial Revolution. These institutions, developed rapidly before and during the Industrial Revolution in Britain, were unfortunately mostly not in place in contemporary China.

Cross-Country Evidence of Patent Laws' Effect on Invention Rates

Economists generally agree that good institutions are important for long-run economic performance (e.g., North, 1990; Acemoglu et al., 2001). However, there is far less agreement about exactly what institutions are good. Patent law is a salient example. The debate over patent law is old. This controversy reached such a height during 1850-1875 that the Netherlands repealed its patent law in 1869, which was not reinstated until 1912 (Malchup and Penrose, 1950).

Fundamentally, patent protection is a case of dynamic inconsistency. Before an invention is made, patent protection gives an incentive for innovation (few people dispute this). But once an invention is made, it is socially optimal to get rid of the inventor's monopoly immediately. However, this may discourage future inventions.

The trade-off between static efficiency loss due to temporary monopoly and potential dynamic gain is well known in the optimal patent design literature, where the optimal patent life is found to be either finite (Nordhaus, 1969) or infinite (Judd, 1985; Gilbert and Shapiro, 1990). Yet, surprisingly, there has been very little hard evidence of whether there is "potential dynamic gain," or if there is, how big it is. Recently Boldrin and Levine (2002) found evidence for dynamic net loss. In an excellent survey, MacLeod and Nuvolari (2006) conclude, "No consensus has been reached yet as to whether the emergence of the modern patent systems exerted a favorable impact on inventive activities" (p. 1).

An inherent difficulty in assessing the impact of patent laws on invention rates is that (paradoxically) the patent record is not an appropriate measure of invention rates for this purpose.[17] By definition, the patent count is zero when a country doesn't have a patent law. This certainly doesn't prove anything. As a result, existing evidence in support of patent laws' role in stimulating inventions is largely historical. By examining contemporary literature on inventions, Dutton (1984) observes that many inventors during the British industrial revolution were explicitly motivated by the prospect of profit from patents, and there was a group of "quasi professional inventors" who profitted through selling or licensing their intellectual properties. Similarly, Khan and Sokoloff (2004) (among other papers by Sokoloff and his co-authors) found that the American patent institution provided a key incentive to "great inventors" during 1790-1930 (identified by the Dictionary of American Biography). However, MacLeod (1988) cautions that some patentees took out patents for the sake of recognition (vanity patenting), and a large volume of inventive activities were undertaken outside the patent system.

Using data from 1851 and 1876 World Exhibitions, Moser (2005b) shows that patent laws had a significant impact on the *direction* of inventions in such a way that inventors

[17] For limitations of patent record as a measure of invention rates under a general context, see Griliches (1990).

in countries without patent protection focused on a small set of industries where secrecy is important while inventions in countries with patent protection were much more diversified. However, as pointed out by Moser (2005b), exhibition data have very little to say about patent laws' impact on the overall invention rates, because of the subjective restrictions placed by the host country on participating countries' exhibition spaces.

To get around the above issues of measuring invention rates consistently before and after the establishment of patent laws, two datasets of major invention counts are used in this study. The main dataset was from Clarence Streit's book, Freedom Against Itself (1954), which contains 1,012 "major inventions, discoveries and innovations" during 1750-1950 worldwide. As a robustness check, a smaller dataset from Funk & Wagnalls New Encyclopedia (2007) was also used, which includes 115 major inventions from 1590-1900. Therefore, this study presents rare cross-country statistical evidence on the positive effect of patent laws on invention rates. A Poisson regression and a negative binomial regression are applied to these two datasets of major invention counts for the US and 14 Western European countries. The data point to a significant positive effect of patent laws on invention rates, after controlling for each country's economic size. The result is robust in different fixed effects and/or random effects specifications and after dropping the UK and the US from the sample.

A Simple Theoretical Framework

As a simple theoretical framework, we assume that the number of major inventions that a country makes in a particular year follows a Poisson distribution. Furthermore, the Poisson arrival rate λ_{it} depends on a country's R&D input. Specifically, consider the following knowledge/invention production function for country *i* in year *t* that is often used in the endogenous growth literature (e.g., Romer, 1990; Jones, 1995):

$$\lambda_{it} = \delta(R\,\&\,D_{it})^{\beta} \ . \tag{3.2}$$

Theoretically, we expect $0 < \delta$ and $0 < \beta < 1$, since $\beta \geq 1$ implies the counterfactual scale effect (i.e., larger R&D input leads to higher growth rate), which is strongly rejected by data (Jones 1995). Taking natural log and rearranging, we get:

$$\log(\lambda_{it}) = \log\delta + \beta\log\left(\frac{R\,\&\,D_{it}}{GDP_{it}}\right) + \beta\log(GDP_{it}) . \tag{3.3}$$

Now assume that a country's research intensity $\left(\frac{R\,\&\,D_{it}}{GDP_{it}}\right)$ depends linearly on its patent law dummy LAW_{it}, a country-specific/time-invariant constant term and an error term:

$$\log\left(\frac{R\&D_{it}}{GDP_{it}}\right)=\eta_i+\eta LAW_{it}+u_{it}. \tag{3.4}$$

Then we obtain the relationship:

$$\log\lambda_{it}=\alpha_i+\beta\log(GDP_{it})+\gamma LAW_{it}+\varepsilon_{it}. \tag{3.5}$$

An alternative formulation is to split GDP into GDP per capita and population:

$$\log\lambda_{it}=\alpha_i+\beta_1\log(POP_{it})+\beta_2\log(GDPC_{it})+\gamma LAW_{it}+\varepsilon_{it}, \tag{3.6}$$

where *GDPC* is GDP per capita. Equation (3.6) reduces to equation (3.5) if $\beta_1=\beta_2$. However, log of GDP per capita and log of population are relatively highly correlated in our sample with a correlation coefficient of 0.40.[18] This mild colinearity makes estimates less reliable. For example, the log of GDP per capita often turns up with a wrong negative sign. Although the effect of patent laws is robust under both specifications, we only report specification (3.5) in this study to save space.

[18] This may be due to weak scale effect, i.e., output per worker depends positively on the population size in the long run. Or it may be due to a Malthusian effect, i.e., higher income leads to a higher fertility rate. Probably both effects are present.

Data

Streit's List of Major Inventions During 1750-1950

The main dataset of major invention counts are taken from Clarence Streit's book, Freedom Against Itself (1954), which includes a total of 1,012 major scientific discoveries, inventions and innovations during 1750-1950. Streit's motivation for compiling such a long list was to show that free societies were more innovative than those that weren't free. His book also includes a list of 70 experts and specialists in many fields all over the world that he consulted in creating this list. However, Streit's list as it stands is too broad for our purpose, since it includes many scientific discoveries (e.g., chemical elements) and theories (e.g., quantum mechanics), political (e.g., suffrage), financial and social innovations (e.g., income tax, unemployment insurance), which were not relevant for our study of the role of patent laws. After removing irrelevant discoveries and social innovations, we end up with total of 614 major inventions (Appendix E).

Most inventions were made by the US and Western European countries, and most countries (including almost all developing countries) do not have any invention on Streit's list. We chose 15 countries (the US and 14 Western European countries[19]) to be included in our sample to form a relatively homogeneous group in institutions, scientific

[19] Our working definition of Western Europe includes Sweden, Norway and Finland.

development, and human capital endowment. If we include developing countries in the sample, the homogeneity of the sample would be compromised. (See more discussion about endogeneity and omitted variables below.) Furthermore, adding developing countries would only strengthen our case of patent laws' positive impact on invention rates, since most developing countries established patent laws very late and had no inventions on the list.

Countries with inventions on this list that are nevertheless excluded from our sample include Russia (9 inventions), Japan (2 inventions), Brazil (2 inventions), India (2 inventions), Canada (2 inventions), and Hungary (1 invention). Their contributions were minor. They are left out of our sample intentionally to maintain relative homogeneity across countries. Russia and Hungary do not belong to Western Europe, and Russia became a communist country in 1917. Japan was essentially a closed economy until 1854. Brazil and India were developing countries during our sample period. Canada didn't become a unified country until 1867. Similarly, Australia didn't become a nation until 1901 and is excluded. Other issues in Streit's list include joint inventions, simultaneous inventions and inventions spanning multiple years.

Joint inventions: Streit (1954) gave the credit of inventing atomic pile in 1942 to both Italy (Enrico Fermi) and the US (Walter Zinn and Herbert Anderson). It is well known that the work was undertaken in Chicago and had nothing to do with Italy, although Enrico Fermi was from Italy. As a correction, it is only counted as an American invention in this case. This was the only joint invention in Streit's list with inventors of different nationalities.

Simultaneous inventions: On the other hand, simultaneous or contested inventions conducted by different people in different countries were counted separately for all countries involved. For example, the invention of the jet engine went to both Italy (Campini Caproni) and Britain (Frank Whittle) in 1940 and 1941 respectively.[20]

Inventions spanning multiple years: When Streit (1954) lists an invention as spanning multiple years, say, 1892-1894, the invention time is uniformly set to the earliest year, i.e., 1892 in this case.

See Table 6 for a summary of data. Figure 12 provides a time series plot of the total number of annual major inventions from Streit (1954). Due to the subjectivity of creating major invention counts, we cannot infer whether the rate of invention has changed over time.

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[20] Other simultaneous inventions in Streit (1954) were "Vitamin C, synthesized" (US, UK and Switzerland) in 1930, "Automobile, gasoline, improved" (Germany, France, US and Austria) in 1892, "Aluminum electrolytic process" (US and France) in 1886, "Photograph, high speed" (UK and US) in 1880, "Automobile, gasoline (contested)" (Germany and Austria) in 1875, "Rifling, gun" (Italy and Sweden) in 1846, and "Steam engine, high pressure" (US and UK) in 1799.

Table 6

Sample Countries' Major Inventions and Patent Laws

Country	# of Major Inventions during 1590-1900	# of Major Inventions during 1750-1950	Year Patent Law Enacted
Austria	1	8	1810
Belgium	0	2	1817
Denmark	0	1	1894
Finland	0	0	1898
France	15	93	1791
Germany	16	77	1815
Italy	6	14	1859
Netherlands	3	1	1817 (repealed in 1869, reinstated in 1912)
Norway	0	0	1834
Portugal	0	0	1837
Spain	0	1	1820
Sweden	2	7	1834
Switzerland	0	9	1888
UK	32	145	1623
US	40	256	1790
Total	115	614	-

Source: Numbers of major inventions during 1590-1900 are from Funk & Wagnalls New Encyclopedia (2007). Numbers of major inventions during 1750-1950 are from Streit (1954). Population and GDP per capita (not listed here) are from Maddison (2001). Most patent law data are from Penrose (1951).

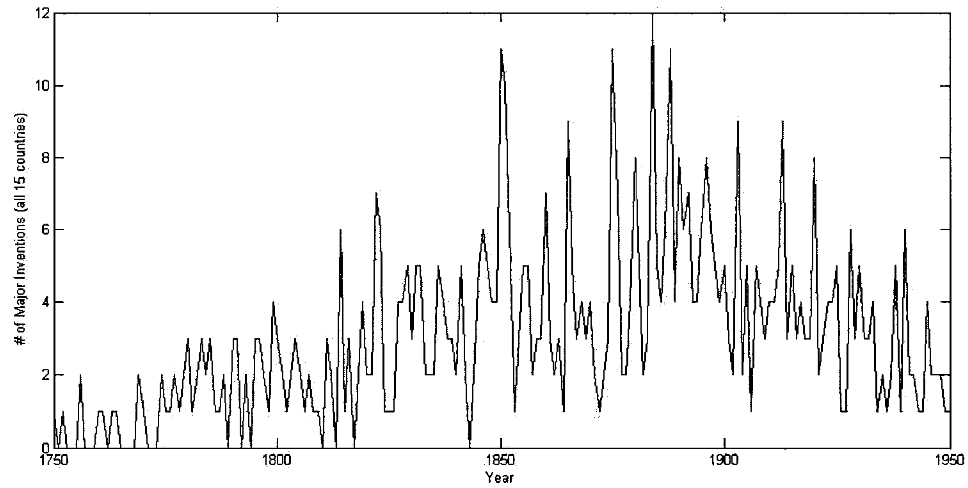

Figure 12. The total numbers of inventions for all 15 countries during 1750-1950. Data source: Streit (1954).

The Encyclopedia List of Major Inventions During 1590-1900

Funk & Wagnalls New Encyclopedia (2007) provides a smaller dataset of major invention counts with a total of 115 major inventions during 1590-1900. A smaller dataset means that a more stringent standard is applied when selecting major inventions. Because of the subjectivity of what inventions to include (see more discussion below), this second dataset is used more as a robustness check. The results from these two datasets are remarkably similar, although they were created by different people for different purposes at different times. Figure 13 provides a time series plot of the total number of annual major inventions from Streit (1954).

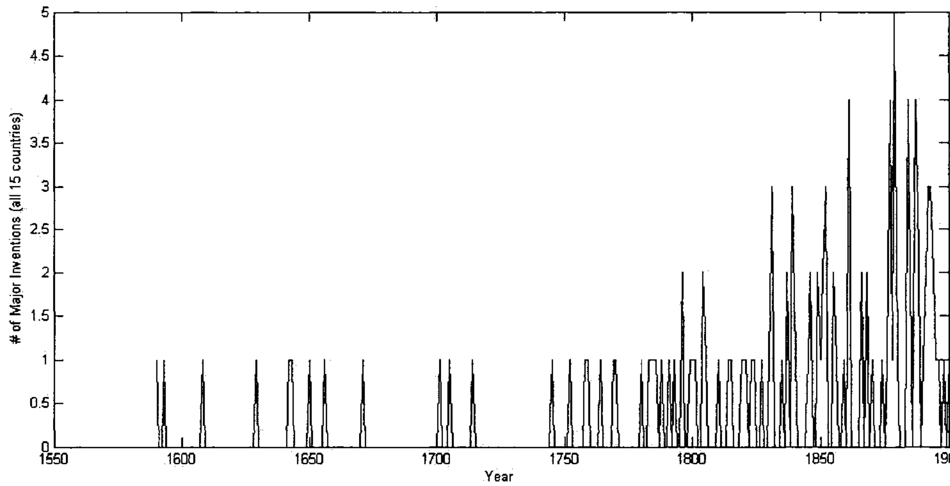

Figure 13. The total numbers of inventions for all 15 countries during 1590-1900. Data source: Funk & Wagnalls New Encyclopedia (2007).

Patent Law Data

Most patent law data (i.e., when patent laws were first established) are from Penrose (1951), which include Austria, Belgium, France, Portugal, Spain, Sweden, the UK and US. Sources for the other seven countries are below.

Germany: Germany didn't become a unified country until 1871. However, according to Penrose (1951), Prussia (which accounts for about 60% of the German territory) established its first patent law in 1815, Wurttemberg in 1836, and Saxonia in 1843. On the other hand, Khan (2006) shows German patent record starting as early as 1811. Lerner (2005) also uses Prussia to proxy for Germany. As a compromise, we set 1815 to be the year when Germany first established a patent law.

Switzerland and the Netherlands: Data are from Khan (2006). The Netherlands is the only country in our sample that repealed its patent law in 1869 (first established in 1817), and it reinstated it in 1912.

Finland: A patent law was first established in 1898, according to the International Encyclopedia of Laws (1999).

Denmark: According to the Danish Patent and Trademark Office, a patent law was first established in 1894. This was independently confirmed by a Danish intellectual property attorney, who gave me a reference in Danish: "Mogens Koktvedgaard and Lise Østerborg," The Danish Patents Act, 2nd rev. edition, 1979, page 21.

Italy: According to an intellectual property attorney practicing in Italy consulted by e-mail, Italy established its first patent law in 1859 (Law No. 3731 of October 30, 1859).

Norway: According to an intellectual property attorney practicing in Norway consulted by e-mail, the first Norwegian patent law was established in June 1885. However, in 1814 Norway became part of Sweden, which adopted a patent law in 1834. To be conservative, I set 1834 as the year when Norway established its patent law, since Norway had zero inventions on Streit's list. Furthermore, Lerner (2005) also indicated Norway as having a patent law in 1850.

GDP and Population Data

GDP per capita and population data are taken from Maddison (2001) for years 1500, 1600, 1700, 1820, 1870, 1913 and 1950. Exponential interpolation (i.e., assuming a fixed growth rate between two points) is then performed to fill in the interim years so that there are data for every year from 1590-1950. Being almost deterministically generated, these data are therefore not subject to the unit root problem that often plagues macroeconomic data.

Econometric Issues

Before we proceed with estimation, there are a number of econometric issues that we need to deal with first.

Does It Matter Whether Inventions Were Actually Patented?

Certainly many inventions were made before national patent laws were enacted, and many inventions were made outside the patent system even after patent laws were introduced. But we are interested in whether patent laws spur inventive activities. Theoretically, the existence of a patent law gives an additional option value to any invention (Pakes 1986). Without a patent law, an invention is only beneficial through secrecy. If the cost of imitation is low, then secrecy may not be effective. This is probably true for most of the mechanical inventions during the Industrial Revolution. With a patent law, an individual or a firm can choose to patent his invention or not. If he chooses not to patent, this does not mean that the patent law has no effect on whether he undertakes the research in the first place. He might intend to patent his invention at the beginning, but in the end find out that he would be better off to keep it as a trade secret. Therefore, it doesn't matter whether inventions were actually patented or not in our sample.

Endogeneity and Omitted Variables

Whether and when a country chooses to enact a patent law is certainly endogenous, and this is a potentially serious issue. For example, countries that are more inventive might choose to establish their patent laws earlier. In that case, causation would go from invention rates to patent laws, not vice versa. The patent law dummy is obviously a government policy variable. Then Dani Rodrik's critique, "Why We Learn Nothing from Regressing Economic Growth on Policies," due to the endogeneity of government policies, applies (Rodrik, 2005).

Lerner (2002) found that political systems and legal traditions played important roles in shaping national patent laws in his 60-country sample over 150 years. Citing historical records, Moser (2005b) indicated that patent systems were initially adopted in a relatively ad hoc manner, and the influence of innovation on patent laws was limited. In our specific setting, this endogenous variable patent law is a special dummy variable, a nondecreasing sequence of zeros and ones.[21] Then only the exact timing of patent law enactment matters, which is a large random event or at least not tied to a country's inventiveness. For example, the British patent statute of 1623 was largely a byproduct of restraining the monarch's arbitrary authority of granting monopolies. America adopted its first patent law in 1790, as mandated by its 1787 constitution. The French revolution (itself a random event) gave birth to the first French patent law in 1791 and spread the influences of French laws throughout Europe. The Netherlands' unique case – a patent law first established in 1817, repealed in 1869, and reinstated in 1912 – shows that the timing of enacting a patent law is more dependent on the current political tides than the stages of economic development. Therefore, at least we have reasons to believe that the issue of endogeneity is not so severe. However, this is still a potential limitation of this study, and it would be desirable if an instrumental variable could be found in future research.

Furthermore, there are certainly omitted variables related to invention rates that aren't included, such as scientific development, education, and other invention-related institutions, such as copyright laws, trade secret laws, etc. To the extent that these omitted variables are correlated with the patent law dummy, then our estimate would not be consistent. We partially circumvent this problem by including only the US and 14 Western European countries in our sample in the hope that the state of scientific development and other legal and institutional aspects were relatively homogeneous

[21] The only exception is the Netherlands, since it abolished its patent law during 1869-1912.

among these countries. Essentially, we are conditioning on these omitted variables. Also, we use a fixed effects model to account for these individual country differences, which is consistent since the observation periods are large (311 and 201 years respectively).

Subjectivity of Counting Major Inventions

Certainly subjectivity is a concern for any man-made list of major inventions. For example, since Streit (1954) created his list to prove that free countries were more innovative, it is possible that he intentionally or unintentionally undercounted innovations from not-so-free countries. However, since all 15 countries in our sample are "free countries" according to Streit's standard, this should not be a problem. Since these two invention count datasets were not created to measure the effect of patent laws on inventions, it is unlikely that the authors would knowingly or unknowingly lower the selection standard to include more inventions from countries with patent laws. So it is unlikely to have any systematic bias on this regard. Last but not least, the results from these two datasets created by different people for different purposes at different times are very similar in pointing to a robust effect of patent laws on invention rates.

The Quality of Patent Laws

Certainly not all patent laws are the same. There were significant differences in the contents and enforcement of patent laws across countries and over time, such as patent length, patent application fee, and whether prior examination is required. For example, the US patent law of 1790 was very different from the British patent statue of 1623 or the French patent law of 1791. Within the US, the patent law was different before and after the 1836 Act (Smith, 1890). Lerner (2002) documented the differences of different national patent systems in many dimensions over time. Unfortunately, we can't take into account variations in patent law quality in this panel data setting. As a remedy, these differences would be picked up by the country fixed effects model, through the fact that unobservables that do not change through time are accounted for in the fixed effect term.

Appropriate Regression Technique

Since the dependent variable is count data, ordinary least square is not appropriate to accommodate nonnegative data with a skewed distribution. The Poisson regression is a natural choice. A casual inspection of both invention datasets reveals that their sample variances (0.65 and 0.19 for Streit's list and the encyclopedia list respectively) are significantly larger than their sample means (0.20 and 0.03 for Streit's list and encyclopedia list respectively), which is inconsistent with the Poisson model with equal mean and variance.

To deal with this overdispersion, we consider the negative binomial regression, which generalizes the Poisson regression to take into account cross-sectional heterogeneity. The derivation of the negative binomial regression comes from the error component model by assuming each country has its unique error term, hence it is a random effects model when it is not augmented with country dummies. The use of a Poisson regression with country dummies constitutes a fixed effects model. Finally, the use of a negative binomial regression with country dummies accommodates both random effects and fixed effects.

Since the negative binomial regression nests the Poisson regression as a special case, our strategy is to run negative binomial regression and then test whether the model can be reduced to the Poisson regression by a likelihood ratio test. We ran a pooled regression as a benchmark (which is strongly rejected by the data). Both the Poisson and binomial regressions are carried out through maximum likelihood estimation.

The Effect of Patent Laws on Inventions: Regression Results

Table 7 reports regression results for the Streit's list. In all the regression specifications, the patent law dummy and the log of GDP have positive signs and are significant at the 1% level and appear to be very robust. In all specifications, the coefficient estimates for the log of GDP are within the theoretical range of $0 < \beta < 1$ mentioned earlier.

Table 7

Regression Results for 614 Inventions During 1750-1950

Dependent Variable INV (Number of Inventions) # of observations: 3,015

Independent Variables	(1) Pooled (Poisson)	(2) Fixed Effects (Poisson)	(3) Random Effects (Negative Binomial)	(4) Fixed & Random (Negative Binomial)	(5) Dropped UK & US
Constant	-9.60(.33)**	-2.80(.34) **	-10.15(.36) **	-2.77(.35) **	-.63(.99)
Log(GDP)	0.68(.03) **	0.17(.03) **	0.74(.04) **	0.17(.03) **	-.12(.10)
Law	1.11(.22) **	1.24(.22) **	1.01(.22) **	1.23(.22) **	1.39(.29)**
Austria		-2.99(.36) **		-2.98(.36) **	-2.61(.40) **
Belgium		-4.41(.71) **		-4.40(.71) **	-3.92(.72) **
Denmark		-4.53(1.00) **		-4.53(1.00) **	-4.23(1.02) **
Finland		-16.57(.15) **		-17.04(.15) **	-17.62(.30) **
France		-.96(.13) **		-.94(.13) **	-
Germany		-1.07(0.15) **		-1.06(.15) **	-.07(.17)
Italy		-2.49(.27) **		-2.46(.27) **	-1.55(.28) **
Netherlands		-4.86(1.00) **		-4.84(1.00) **	-4.4(1.06) **
Norway		-16.97(.14) **		-17.41(.15) **	-17.95(.33) **
Portugal		-17.15(.13) **		-17.50(.14) **	-17.86(.28) **
Spain		-5.19(1.00) **		-5.18(1.00) **	-4.52(1.01) **
Sweden		-3.00(.38) **		-3.00(.38) **	2.63(.41) **
Switzerland		-2.44(.33) **		-2.43(.34) **	-2.02(.39) **
UK		-.68(.12) **		-.65(.12) **	-
US		-		-	-
Pseudo R^2	0.27	0.43	0.19	0.34	0.30

Note: Robust standard errors are in parentheses. ** and * indicate significance at 1% and 5% respectively. In the last column, "Dropped UK & US," the sample size is 2,613.

A likelihood ratio test strongly rejects pooled Poisson regression (first column in Table 7) in favor of fixed effects Poisson regression (second column in Table 7). Specifically, $-2(\log L_R - \log L_U) = 564.27$, which is much greater than $\chi^2_{14}(1\%) = 29.14$.

The random effects model with a negative binomial regression (third column in Table 7) gives similar coefficient estimates for both the patent law dummy and the log of GDP, as compared with the pooled Poisson regression. The 95% confidence interval for θ is [0.93, 1.70], which doesn't include zero ($\theta = 0$ corresponds to the Poisson regression). Therefore, we shall use negative binomial regression instead of the more restrictive Poisson regression (see Greene, 2003, Chapter 21).

Column 4 in Table 7 presents the fixed and random effects model, i.e., negative binomial regression with country dummies, which is our preferred regression model that accommodates both the random effects and fixed effects. The coefficient estimates are very similar to those from the fixed effects model (i.e., Poisson regression with country dummies). Again the data rejects the reduction to the restrictive Poisson fixed effects regression, since the 95% confidence interval for θ is [0.13, 0.48], which doesn't include zero ($\theta = 0$ corresponds to Poisson regression).

A likelihood ratio test rejects the random effects model (i.e., negative binomial regression without country dummies) in favor of the fixed and random effects model. Specifically, $-2(\log L_R - \log L_U) = 461.63 > \chi^2_{14}(1\%) = 29.14$. Therefore, the presence of fixed effects and random effects are both supported by the data.

Since both the United Kingdom and the United States contributed many inventions and they both established a patent law very early, one might wonder how much of our results are driven by these two countries. Therefore, we drop the UK and the US from our sample in the fixed and random effects model as a robustness check. Although the log of GDP becomes insignificant with the wrong sign, the patent law dummy is still significant at the 1% level.

Since there are many zeros in the invention count data (2635 out of 3015), one is naturally tempted to try the zero-inflated Poisson regression, in which case the patent law dummy becomes insignificant but still with a positive sign. The Vuong statistic (Vuong, 1989) is 24.99, which favors the zero-inflated model in a nonnested test. A zero-inflation negative binomial regression yields similar results with Vuong statistic being 39.29. These results are understandable, since in zero-inflated regressions the probability of zero occurring doesn't depend on the covariates. So we are only left with 380 nonzero observations out of a total of 3,015 observations to explain. It does improve the model's fit. But why would a country's probability of having zero major inventions in a particular year have a separate distribution that doesn't depend on any covariates at all?[22] This doesn't make much sense theoretically. Hence, we do not take ad hoc zero-inflated models seriously.

[22] The usual way to justify using the zero-inflated Poisson or negative binomial regression is that agents make decisions in two stages, first decide either zero or nonzero, then decide how many if nonzero in the first stage. This scenario clearly doesn't apply here.

Table 8 reports regression results for the encyclopedia list, which are essentially parallel with the results from Streit's list. In fact the coefficient estimates are pretty similar across datasets. Again, in all regression specifications, the patent law dummy and the log of GDP have positive signs and are significant at 5% level or 1% level.

A likelihood ratio test strongly rejects a pooled Poisson regression (first column in Table 8) in favor of a fixed effects Poisson regression (second column in Table 8). Specifically, $-2(\log L_R - \log L_U) = 69.70$, which is much greater than $\chi^2_{14}(1\%) = 29.14$.

The random effects model with a negative binomial regression (third column in Table 8) gives similar coefficient estimates for both the patent law dummy and the log of GDP, as compared with the pooled Poisson regression. The 95% confidence interval for θ is [0.33, 2.40], which doesn't include zero ($\theta = 0$ corresponds to the Poisson regression). Therefore, the negative binomial regression is favored against the Poisson regression.

Column 4 in Table 8 presents the fixed and random effects model, i.e., negative binomial regression with country dummies, which is our preferred regression model that accommodates both the random effects and fixed effects. The coefficient estimates are very similar to those from the fixed effects model (i.e., Poisson regression with country dummies). Again the data rejects the reduction to the restrictive Poisson fixed effects regression, since the 95% confidence interval for θ is [0.10, 1.53], which doesn't include zero ($\theta = 0$ corresponds to the Poisson regression).

Table 8

Regression Results for 115 Inventions During 1590-1900

Dependent Variable INV (Number of Inventions) # of observations: 4,665					
Independent Variables	Pooled (Poisson)	Fixed Effects (Poisson)	Random Effects (Negative Binomial)	Fixed & Random (Negative Binomial)	Dropped UK & US
Constant	-7.04(.32)**	-4.46(.35)**	-7.06(.32)**	-4.49(.35)**	-4.64(1.23)**
Log(GDP)	1.06(.09)**	.69(.08)**	1.07(.09)**	.71(.09)**	.28(.39)
Law	.85(.28)**	.64(.30)*	.84(.28)**	.62(.30)*	1.13(.52)*
Austria		-2.59(1.03)*		-2.57(1.03)*	-2.03(1.42)
Belgium		-17.55(.23)**		-18.28(.23)**	-17.97(.78)**
Denmark		-15.62(.32)**		-17.46(.32)**	-17.23(1.10)**
Finland		-14.38(.35)**		-16.98(.35)**	-16.94(1.38) **
France		-1.40(.33)**		-1.41(.33)**	-
Germany		-1.18(.30)**		-1.19(.30)**	.21(.36)
Italy		-1.84(.43)**		-1.84(.43)**	-.48(.47)
Netherlands		-1.52(.59)**		-1.49(.59)*	-.80(.79)
Norway		-16.61(.32)**		-17.30(.33)**	-7.37(1.36) **
Portugal		-17.92(.28)**		-17.82(.28)**	-17.69(1.03)**
Spain		-19.35(.21)**		-18.82(.21)**	-18.31(.47)**
Sweden		-1.57(.75)*		-1.54(.75)*	-1.12(1.12)
Switzerland		-16.43(.29)**		-17.76(.29)**	-17.42(.93)**
UK		-.79(.24)**		-.78(.24)**	-
US		-		-	-
Pseudo R^2	0.29	0.35	0.26	0.32	0.25

Note: Robust standard errors are in parentheses. ** and * indicate significance at 1% and 5% respectively. In the last column, "Dropped UK & US," the sample size is 4,043.

A likelihood ratio test rejects the random effects model (i.e. negative binomial regression without country dummies) in favor of the fixed and random effects model. Specifically, $-2(\log L_R - \log L_U) = 65.34 > \chi^2_{14}(1\%) = 29.14$. Therefore, the presence of both fixed effects and random effects is supported by the data.

Again we drop the UK and the US from our sample in the fixed and random effects model as a robustness check in the fixed and random effects model. As reported in the last column of Table 8, although the log of GDP becomes insignificant (this time with a right sign), the patent law dummy is still significant at 5% level.

In summary, this study presents (to our knowledge) the first cross-country statistical evidence of the importance of patent laws on innovation. Two datasets of major invention counts for the US and 14 Western European countries during 1750-1950 and 1590-1900 respectively were used to assess the impact of patent laws on invention rates. Both datasets point to a significant positive effect of patent laws on invention rates, after controlling for each country's economy size. This result is robust in different specifications of cross-country fixed effects and/or random effects models and dropping the UK and the US from the sample. Regarding the fact that these two invention count datasets were created by different people for different purposes at different times, it is remarkable that they produce essentially the same results.

Could James Watt Be a Chinese? A Case Study

In this section, I ask a hypothetical question: Could James Watt (1736 – 1819) be a Chinese? Or if James Watt were born in China, would he still be able to invent the steam engine? The importance of Watt's invention of the steam engine for the Industrial Revolution is hard to overestimate. Without the steam engine, the Industrial Revolution might have been delayed or much less dramatic. The following biographic materials were mostly taken from Marshall (1925).

Before attending grammar school, James Watt received home education from his mother because his constitution was considered too delicate. In 1754 Watt went to Glasgow to learn the trade of mathematical instrument maker for a year and then went to London as a clockmaker's apprentice for another year before returning to Glasgow to set up his own shop. In 1763, Watt's life made a historical turn when he was asked to fix a Newcomen steam engine for the University of Glasgow. Apparently, his revolutionary ideas came into being following his repair work. Conceiving an idea may cost next to nothing, but putting it to work can be the most challenging thing. As recounted vividly by Marshall (1925):

> For two days he enjoyed the exquisite pleasure of building engines in the world of his imagination....His difficulties began when he started to make a working model. A hundred tiresome problems of detail were revealed which had not existed in the immaterial world of his imagination. (Ch. 5)

All these take money. James quickly found himself borrowing from his friends and running heavily into debts.

> He wanted a few thousand pounds to complete his experiments, build a factory, and manufacture the engines that should persuade the world that he was right. The profits would eventually cover this outlay, but he wanted to spend those profits in advance. (Marshall, 1925, Ch. 5)

His first chance came in 1766, when he went into a partnership with John Roebuck, a leading businessman and inventor in his own right. Roebuck "undertook to pay his outstanding debt of 1,000 pounds and to bear all future cost of experiments and of securing a patent. In return for this he was to have two-thirds of the property of the invention" (Marshall, 1925, Ch. 5). Obviously, Roebuck was fully aware that his partner's invention would be a "property" to be clearly defined and protected by law. Without an effective patent protection, the invention would be worthless, and Roebuck certainly would not have entered into such a partnership.

With Roebuck's critical financial support, in 1769 Watt finally patented his epochal invention. However, before they could produce a commercial steam engine, "the engine was now costing him everything, but it brought him no income." The arduous path from an ingenious patent to a marketable product dragged on for years – only to see Roebuck go bankrupt in 1773 during the British trade depression. Watt took on a side job as a canal surveyor in order to support his wife and two children. Suddenly, their patent seemed worthless, not even recognized by Roebuck's creditors. When things appeared really bad, Watt wrote to his friend, "Of all things in life there is nothing more foolish than inventing" (Marshall, 1925, Ch. 5).

In 1774, Watt's second chance came when he formed his second partnership with Matthew Boulton, an extremely successful manufacturer. Their contract stipulated:

> Boulton held two-thirds of the property in the patent, and undertook to pay all expenses of past and future experiments....The profits were to be divided in the proportions of two-thirds to him and one third to Watt. (Marshall, 1925, Ch. 7)

However, there was another serious hurdle in their joint venture: "The patent was for fourteen years, and six of these had passed before he was in a position to execute a single order" (Marshall, 1925, Ch. 6). They decided to ask the Parliament for an extension, which was granted in 1775 into a total of 25 years. "Boulton now felt that he could safely embark on manufacture on an extensive scale" (Marshall, 1925, Ch. 6). In 1776, their first steam engine was sold. However, it was only by 1783 that their steam engine business became profitable.

> Twenty years had passed since Watt conceived the idea of his engine, forty thousand pounds had been invested by Boulton in the development of the invention, and at last they were beginning to reap the fruits of their labors. (Marshall, 1925, Ch. 7)

Even with a readily enforceable British patent law, "there had always been trouble from pirates who picked up some knowledge of the principle of Watt's engines and made use of it without recognizing their debt to the inventor" (Marshall, 1925, Ch. 8). The importance of patent protection was highlighted when James Watt actually fought with a pirate of his patent (one of their former employees) in court in 1793 and won.

The very fact that James Watt's invention was patentable made his two partnerships possible. In both partnerships, James Watt was able to secure financial support only by selling a significant share of his patent. If patent protection were not credible, neither James Watt nor Roebuck nor Boulton would spend their enormous time, effort and money on this gigantic project. It took James Watt ten years of hard labor, two partnerships, an extension of patent by the Parliament and tens of thousands of pounds to complete his invention and move it onto the market. In short, missing an enforceable patent law, James Watt would not have invented the steam engine if he was born in contemporary China.

China's (Lack of) Legal Tradition

Then the question becomes why a patent law and a legal system in general didn't develop in China. This question is at least as profound as the Needham puzzle. Lin (1995) lamented why the curriculum of Chinese civil service exams did not include science and mathematics, besides moral classics and literature. We may well wonder why there wasn't profession legal training in the curriculum. After all, a major day-to-day function of Mandarin officials was to judge civil and criminal cases instead of conducting or overseeing scientific research. Reading moral classics and literature was a poor preparation for this legal function.

Path dependence may be an important reason for the insignificance of laws in Chinese society. After an unauspicious start in the debate between Confucians and Legalists culminating in the heavy-handed but short-lived Ch'in Dynasty (221-207 B.C.), the reputation of "rule of law" seemed to have been forever tarnished, and China was locked in a preference of "rule of morality" over rule of law, with the latter being only supplementary. The dominant Confucian philosophy emphasizes "obligations" over "rights," which is a key concept in the Western legal tradition.

Certainly there were laws on paper, but they were always secondary to moral persuasion and far from being a central organizing principle of the Chinese society. Chen (1969) argued that "pre-modern Chinese criminal and administrative codes, legal commentaries, and case collections are unsurpassed in quantity and comprehensiveness by the legal heritage of any nation" (p. 275). However, Chen (1969) went on to admit, "Nevertheless, in Chinese legal scholarship, there is not much creative thinking; systematic and analytical treatises are rare" (p. 275).

Harrison (1968) commented on the two features of the Chinese judiciary system:

> I) The vast number of substatutes (1,892 by 1870) resulted in some inconsistencies between statutes and substatutes, and between various substatutes....The punishment, of course, varied depending on which statute the criminal was supposed to have violated. II) Each case was decided on its own merits without automatic references to established precedents. (p. 868)

Bernhardt and Huang (1994) noted "how infrequently court directives make explicit and specific references to statutes (*lu*) or substatutes (*li*)" (p. 125) because magistrates "generally preferred the civil cases be resolved out of court" (p. 138). The judges were poorly trained bureaucrats, and there were no lawyers or jury, prompting Victor Li (1978) to title his book aptly as *Law Without Lawyers*.

The lack of formal institutions in China may not be as critical as far as market integration is concerned. Ma (2004) showed that two of China's largest merchant groups originating in Huizhou and Shanxi were able to successfully engage in long-distance trading or banking through a network of lineage unions or collective punishments for fraudulent behaviors, etc. However, for any potential inventor to make a sizable commitment to R & D investment, this is nearly impossible without a specific definition and enforcement of intellectual property rights.

In an empirical study of 60 countries over a 150-year period, Lerner (2002) showed that a country's legal tradition matters as a determinant of its patent policy even after controlling for national income and democratic institutions.

If we broaden our view to include the whole world and not just China vis-à-vis Western Europe, then we see that traditional institutions in developing countries around the world often did not evolve into more complex, impersonal, formal and legal institutions as in Europe. So the question is not so much why China couldn't develop formal institutions, but rather why Western Europe could and did. The question of why impersonal, formal, and legal institutions failed to develop in China is profound and still largely unanswered (see Levine, 2005, for a survey). This is a critical area where serious future research needs to be undertaken.

Conclusion

The Industrial Revolution depended critically on systematic incentives given to inventors. The enactment of patent laws was a quantum leap by Western Europe to base its inventive activities on deliberate R & D instead of casual learning by doing. This resulted in sustained and accelerated technological progress. Although China led the world technologically in ancient times due to its population size and greater chance of learning by doing, it was far from enough to generate an Industrial Revolution and quickly ran into diminishing returns. The traditional Chinese society was characterized by rule by men or morality instead of rule by law. Without a formal legal tradition, it was difficult to enact and enforce the protection of intellectual properties.

Certainly, the lack of sound legal institutions alone does not explain the complex phenomenon of why the Industrial Revolution didn't happen in China. However, a central contention of this paper is that any meaningful discussion of this fundamental problem has to put the role of legal institutions at the center stage.

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APPENDIX A

SKILLED RETURN MIGRATION FROM US IN 1990

#	Country of Origin	Number of Return Migrants†	Ratio of Skilled Migrants‡	Number of Skilled Return Migrants[1]	Stock of Skilled Immigrants‡	Rate of Skilled Return Migration[2]
1	Argentina	835	54.93%	458.67	35,200	1.30%
2	Colombia	2,337	39.20%	916.10	63,799	1.44%
3	Dominican Republic	2,860	22.60%	646.36	42,451	1.52%
4	Ecuador	1,193	35.37%	421.96	31,596	1.34%
5	El Salvador	1,641	16.87%	276.84	44,465	0.62%
6	Guatemala	846	20.17%	170.64	25,686	0.66%
7	India	5,275	75.08%	3,960.47	228,270	1.73%
8	Iran	3,998	69.93%	2,795.80	105,526	1.68%
9	Jamacia	2,539	41.67%	1,058.00	66,633	1.59%
10	Korea	8,425	53.30%	4,490.53	201,460	2.23%
11	Mexico	20,068	12.66%	2,540.61	347,218	0.73%
12	Peru	526	50.49%	265.58	43,583	0.61%
13	Philippines	11,242	67.69%	7,609.71	493,074	1.54%
14	Trinidad & Tobago	842	46.09%	388.08	30,330	1.28%

† Source: Mulder et al. (2002), Table 5.

‡ Source: Carrington and Detragiache (1998).

1. Number of skilled return migrants = Number of skilled migrants × Ratio of skilled migrants.

2. Rate of skilled return migration = number of skilled return migrants ÷ stock of skilled immigrants

APPENDIX B

MACROECONOMIC DATA DURING 1990-2000

#	Country of Origin	Real Per Capita GDP 1990*	Real Per Capita GDP 2000*	Annual Growth Rate 1990-2000	Average Year of Schooling 1990**
1	Argentina	7218.69	11006.46	0.0431	7.77
2	Colombia	4934.49	5383.46	0.0087	4.37
3	Dominican Republic	3159.75	5270.16	0.0525	4.3
4	Ecuador	3773.98	3467.66	-0.0084	5.94
5	El Salvador	3524.55	4435.17	0.0233	3.58
6	Guatemala	3597.8	3914.2	0.0085	2.6
7	India	1674.96	2478.92	0.04	3.68
8	Iran	3881.75	5994.59	0.0444	3.36
9	Jamacia	4100.42	3692.59	-0.0104	4.55
10	Korea	9952.39	15875.84	0.0478	9.25
11	Mexico	7333.8	8762.34	0.018	5.87
12	Peru	3584.69	4589.04	0.025	5.92
13	Philippines	3009.32	3425.04	0.013	7.07
14	Trinidad & Tobago	8765.17	11175.2	0.0246	6.66

* Source: Penn World Table, Mark 6.1. Available at http://pwt.econ.upenn.edu. Accessed on July 20, 2006.

** Source: Barro and Lee (2001).

APPENDIX C

SKILLED RETURN MIGRATION FROM NEW ZEALAND IN 2001

#	Country of Origin	Stock of Migrants†	Ratio of Skilled Migrants‡	Stock of Skilled Migrants[1]	Skilled Return Migrants‡	Rate of Skilled Return Migration[2]
1	China	24,627	0.1546	3807	170	0.0447
2	Fuji	17,136	0.2119	3631	69	0.0190
3	India	12,220	0.1667	2037	41	0.0201
4	Malaysia	13,211	0.2135	2820	67	0.0237
5	Philippines	5,708	0.3434	1960	34	0.0173
6	Samoa	10,182	0.1300	1323	54	0.0408
7	South Africa	19,364	0.3387	6558	61	0.0093
8	South Korea	14,565	0.5873	8554	463	0.0541
9	Thailand	6,272	0.2647	1660	56	0.0337

† Source: Statistics New Zealand. Available at www.stats.govt.nz/tables/tourism-migration-2001.htm (Table 9.06), accessed on 10/10/06. Using perpetual inventory method, I added up all arrivals and subtracted all departures during 1981-2000 to generate the stock of migrants in 2001.

‡ Source: Statistics New Zealand. Available at www.stats.govt.nz/tables/tourism-migration-2001.htm (Table 9.02), accessed on 10/10/06. I used the proportion of "Administrators and Managers," "Professionals," and "Technicians" in the total arrivals in 2001 to proxy for the ratio of skilled migrants in the total stock of migrants. Skilled return migrants are defined as the return migrants in the above three occupations.

1. Stock of skilled migrants = Stock of migrants × Ratio of skilled migrants.

2. Rate of skilled return migration = Skilled return migrants ÷ Stock of skilled migrants.

APPENDIX D

MACROECONOMIC DATA DURING 2000-2005

#	Country of Origin	Per Capita GNI 2000* (PPP 2000 dollar)	Per Capita GNI 2005** (PPP 2000 dollar)	Annual growth rate 2000-2005***	Average Year of Schooling 2000****
1	China	3920	6600	1.1098	5.74
2	Fuji	4480	5960	1.0588	7.96
3	India	2340	3460	1.0814	4.77
4	Malaysia	8330	10320	1.0438	7.88
5	Philippines	4210	5300	1.0471	7.62
6	Samoa	5050	6480	1.0511	6.65
7	South Africa	9160	12120	1.0576	7.87
8	South Korea	17300	21850	1.0478	10.46
9	Thailand	6320	8440	1.0596	6.1

* Source: World Bank Atlas 2002, Volume 1. Available at www.worldbank.org under "Data & Research, " accessed on 10/10/06.

** Source: World Bank Quick Reference Table. Available at www.worldbank.org under "Data," then "Quick Reference," accessed on 10/10/06.

*** The computed average growth rates of per capita GNI during 2000-2005 are certainly too high due to the fact that PPP dollars in 2000 were worth more than PPP dollars in 2005. However, we do not need to deflate PPP 2005 dollars since it would be multiplying a constant to each entry. For this reason, I do not subtract 1 from the annual growth rate.

**** Source: Barro and Lee (2001).

APPENDIX E

SIX HUNDRED FOURTEEN INVENTIONS FROM STREIT (1954)

1. Iron, coke for coal process (1750, UK)
2. Lightening rod (1752, US)
3. Cement, hydraulic mfg. of (1756, UK)
4. Lens, achromatic (1756, UK)
5. Spectacle, bifocal (1760, US)
6. Percussion (1761, Austria)
7. Chronometer, modern (1763, France)
8. Spinning jenny (1764, UK)
9. Spinning frame (1769, UK)
10. Steam wagon (1769, France)
11. Caterpillar tread (1770, UK)
12. Boring machine (1774, UK)
13. Spinning mule (1774, UK)
14. Electrophorous (1775, Italy)
15. Submarine (1776, US)
16. Mines, submarine (1777, US)
17. Saw, circular (1777, UK)
18. Water closet, improved (1778, UK)
19. Bicycle, earliest (1779, France)
20. Bridge, cast iron (1779,UK)
21. Ammunition, shrapnel (1780, UK)
22. Insemination, artificial, plants (1780, Italy)
23. Pen, steel (1780,UK)
24. Steam engine, compound (1781,UK)
25. Balloon (1782, France)
26. Steam engine, improved (1782,UK)
27. Balloon, hydrogen gas (1783, France)
28. Parachute (1783, France)
29. Steamship (1783, France)
30. Iron, puddling process (1784, UK)
31. Plow, cast iron mold boards (1784,UK)
32. Milling, of flour, 1st automatic (1785,US)
33. Loom, power, water (1785, UK)

34. Propeller, screw (1785, UK)
35. Threshing machine (1786,UK)
36. Ship, iron (1787,UK)
37. Ammunition, explosive shell (1788,UK)
38. Fly ball governor, 1st technical use of feedback principle (1788,UK)
39. Nail-making machine (1790, UK)
40. Optical glass, homogenous (1790, Switzerland)
41. Printing press, rollers used (1790, UK)
42. Planing machine for wood (1791, UK)
43. Printing press, platen, power driven (1791,US)
44. Soda from salt (1791,France)
45. Cotton gin (1793,US)
46. Telegraph, visual (1793,France)
47. Gas lighting, city (1795,UK)
48. Pencil, graphite (1795, France)
49. Canning, food (1795,France)
50. Cement, "roman" (1796,UK)
51. Press, hydraulic (1796,UK)
52. Smallpox vaccine (1796,UK)
53. Carding machine (1797,US)
54. Plow, cast iron (1797,US)
55. Lithography (1798,Germany)
56. Lathe, screw-cutting (1799,UK)
57. Paper-making machine, continuous web (1799,France)
58. Steam engine, high pressure (1799,US)
59. Steam engine, high pressure (1799,UK)
60. Electric cell, copper zinc (1800,Italy)
61. Printing press, all iron (1800,US)
62. Rocket (1800,UK)
63. Mortising machine (1801,UK)
64. Safe, fireproof (1801,UK)
65. Photography, earliest recorded experiments (1802,UK)
66. Loom, steam powered (1803,UK)
67. Paper-making machine, improved (1803,UK)
68. Loom, pattern (1804,France)
69. Propeller, twin screw applied to navigation (1804,US)
70. Torpedo, marine (1804,US)
71. Electroplating (1805,Italy)
72. Warship, iron clad, proposed (1805,UK)
73. Knitting machine, latch needle in (1806,France)
74. Percussion cap and powder (1807,UK)
75. Steamship (1807,US)
76. Saw, band, for wood (1808,UK)
77. Paper-making machine, cylinder (1809,US)
78. Air conditioning, artificial ventilation (1811,UK)

79. Shotgun, breach loading (1811,US)
80. Tunnelling, modern process (1811,UK)
81. Electric cell, storage (1812,Germany)
82. Printing press, rotary, first practical (1812, Germany)
83. Heliography (1814,France)
84. Kaleidoscope (1814,UK)
85. Locomotive, steam (1814,UK)
86. Newspaper, power printed (1814,UK)
87. Planimeter (1814,Austria)
88. Steam jet (1814,UK)
89. Meter, dry gas (1815,UK)
90. Bicycle, "hobbyhorse" (1816,France)
91. Knitting machine (1816,UK)
92. Lamp, miner's safety (1816,UK)
93. Milling machine (1818,US)
94. Tunnel shield (1818,UK)
95. Auscultation, stethoscope (1819,France)
96. Diving suit (1819,UK)
97. Lathe, turning irregular wood forms (1819,US)
98. Plow, cast iron, standard (1819,US)
99. Calculating machine (1820,France)
100. Electroscope (1820,Germany)
101. Carborundum (1821,US)
102. Dynamo, electric current into mechanical motion (1821,UK)
103. Calculating machine, binary system (1822,UK)
104. Galvanometer (1822,Germany)
105. Photography, first experiments (1822,France)
106. Pen, steel, machine made (1822,UK)
107. Printing, multicolored (1822,US)
108. Steel alloy (1822,UK)
109. Type-setting machine (1822,US)
110. Ammunition, cylindrical-conoidal projectile (1823,UK)
111. Binoculars, modern (1823,Austria)
112. Engine, gas, vacuum (1823,UK)
113. Gases, liquefaction and solidification of (1823,UK)
114. Lens, lighthouse (1823,France)
115. Electro-magnet, forerunner (1823,UK)
116. Cement, Portland (1824,UK)
117. Railroad, commercial (1825,UK)
118. Limelight (1826,UK)
119. Aluminum, reduction of (1827,Germany)
120. Differential gear for road vehicle (1827,France)
121. Match, friction (1827,UK)
122. Turbine, hydraulic (1827,France)
123. Iron, hot air blast in mfg. of (1828,UK)

124. Locomotive, tubular boiler (1828,France)
125. Spinning ring frame (1828,UK)
126. Urea, synthesis (1828,Germany)
127. Braille system for blind (1829,France)
128. Filtration, city water (1829,UK)
129. Sewing machine (1829,France)
130. Stereotyping, papier mache (1829,France)
131. Typewriter (1829,US)
132. Cannon, breech loading (1830,France)
133. Heat of the earth utilized (1830,France)
134. Loom, embroidery stitch (1830,Switzerland)
135. Dynamo, homopolar (1831,UK)
136. Electromagnet, improved (1831,US)
137. Match, phosphorous (1831,France)
138. Mowing machine (1831,US)
139. Sulphuric acid, contact process (1831,UK)
140. Chloral hydrate, a narcotic (1832,Germany)
141. Dynamo, heteropolar (1832,France)
142. Dynamo, significant improvement (1832,UK)
143. Propeller, screw, improved (1832,France)
144. Telegraph, electro-magnetic recording (1832,US)
145. Plow, steel (1833,US)
146. Reaper, reciprocating saw-tooth cutter for (1833,US)
147. Aniline dye in coal tar (1834,Germany)
148. Carbolic acid (1834,Germany)
149. Elevator, safety (1835,UK)
150. Revolver (1835,US)
151. Acetylene (1836,UK)
152. Morse code (1836,US)
153. Propeller, screw, improved (1836,US)
154. Rifle, breech loading (1836,Germany)
155. Road surfacing (1836,UK)
156. Dynamo, significant improvement (1837,UK)
157. Iron, galvanized, hot dip (1837,UK)
158. Telegraph, electric (1837,UK)
159. Shorthand (1837,UK)
160. Daguerreotype (1838,France)
161. Drop hammer, steam (1838,UK)
162. Stereoscope (1838,UK)
163. Babbitt metal (1839,US)
164. Photography, printing from paper negatives (1839,UK)
165. Rubber, vulcanized (1839,US)
166. Bicycle, with pedals and in metal (1840,UK)
167. Bridge, suspension, steel cable (1840,US)
168. Electric cell, carbon zinc (1841,Germany)

169. Insect control (1841,US)
170. Lamp, incandescent, carbon powder (1841,UK)
171. Pneumatic caisson (1841,France)
172. Seismometer (1841,UK)
173. Fertilizer, super phosphate (1842,UK)
174. Mercerized textiles (1842,UK)
175. Anesthesia, nitrous oxide (1844,US)
176. Telegram, first sent (1844,US)
177. Lamp, arc, first patent (1845,UK)
178. Lamp, metallic filament (1845,US)
179. Lathe, turret (1845,US)
180. Printing press, rotary, double cylinder (1845,US)
181. Tire, pneumatic (1845,UK)
182. Ammunition, metallic cartridge, practical (1846,France)
183. Anesthesia, ether (1846,US)
184. Guncotton (1846,Germany)
185. Rifling, gun (1846,Italy)
186. Rifling, gun (1846,Sweden)
187. Sewing machine, improved (1846,US)
188. Ammunition, pin cartridge (1847,France)
189. Building, iron (1847,US)
190. Nitroglycerin (1847,Italy)
191. Steam engine, regenerative (1847,Germany)
192. Steel beam (1847,France)
193. Alkyl-anilines (1848,Germany)
194. Gastrotomy (1848,France)
195. Hydrocarbons, synthesis (1848,Germany)
196. "Piqure" (1848,France)
197. Folding boat (1849,UK)
198. Rock drill, powered (1849,US)
199. Steam pressure gauge (1849,France)
200. Turbine, hydraulic, improved (1849, US)
201. Calculating machine, keyboard (1850,US)
202. Embroidery machine (1850,Switzerland)
203. Lamp, fluorescent (1850,Germany)
204. Paraffin oil, distillation (1850,UK)
205. Photography, collodion process, wet (1850, UK)
206. Anthrax bacillus (1850,France)
207. Benzyl alcohol, benzyl chloride (1850,Italy)
208. Ether manufacture (1850,US)
209. Fats and glycerides, synthesis (1850,France)
210. Iron molding machine (1850,UK)
211. Tractor, steam (1850,US)
212. Cable, first submarine, English channel (1851,UK)
213. Envelope-making machine (1851,UK)

214. Lithophone (1851,France)
215. Locomotive, electric (1851,US)
216. Ophthalmoscope (1851,Germany)
217. Photogrammetry (1851,France)
218. Photo-lithography (1851,France)
219. Refrigeration machine (1851,US)
220. Rhumkorff coil (1851,Germany)
221. Rifle, breech loading, improved (1851,US)
222. Airship, steam-powered (1852,France)
223. Fluorescence, discovered (1852,UK)
224. Gyroscope (1852,France)
225. Mining, hydraulic (1852,France)
226. Photography, half-tone printing process (1852,UK)
227. Telegraph, wire, duplex (1853,Austria)
228. Planimeter, polar (1854,Switzerland)
229. Rock drill, diamond (1854,US)
230. Ticker-tape machine (1854,US)
231. Gas burner (1855,Germany)
232. Match, safety (1855,Sweden)
233. Steel, pneumatic process (1855,UK)
234. Aniline dye, mauve, synthesis (1856,UK)
235. Lamp, coal oil, first (1855,US)
236. Rubber dental plate (1855,US)
237. Dynamo, shuttle winding (1856,Germany)
238. Furnace, regenerative (1856,UK)
239. Furnace, regenerative (1856,Germany)
240. Milk, condensed (1856,US)
241. Engine, electric ignition (1857,Italy)
242. Warship, ironclad, built (1857,France)
243. Boiler, feed injector for (1858,France)
244. Cable car (1858,US)
245. Photography, aerial (1858,France)
246. Binoculars, prism (1859,France)
247. Electric cell, storage (1859,France)
248. Spectroscope, prism (1859,Germany)
249. Dynamo, direct current, ring winding (1860,Italy)
250. Linoleum (1860,UK)
251. Pneumatic tube system (1860,UK)
252. Refrigeration, ammonia absorption (1860,France)
253. Sewing machine, shoes (1860,US)
254. Fertilizer, potassium (1860,Germany)
255. Rhinoscopy (1860, Germany)
256. Colloids (1861,UK)
257. Furnace, electric arc (1861,UK)
258. Gun, gatling (1861,US)

259. Acetylene from calcium carbide (1862,Germany)
260. Powder, smokeless, one of first (1862,Germany)
261. Cardiograph (1863,France)
262. Sleeping-car (1863,US)
263. Solvay process, caustic soda (1863,Belgium)
264. Binding machine, grain (1864,US)
265. Bicycle, front wheel drive, “bone breaker” (1865,France)
266. Block signals, railway (1865,US)
267. Pneumatic tool (1865,UK)
268. Printing press, web-feeding (1865,US)
269. Steel, Martin process, fuse steel (1865,France)
270. Antiseptic surgery (1865,UK)
271. Refrigerator car, railway (1865,US)
272. Steam roller (1865,US)
273. Welding, electric (1865,US)
274. Cable, transatlantic (1866,US)
275. Steel, by open hearth (1866,UK)
276. Pasteurization (1866,France)
277. Rock drill, pneumatic (1866,US)
278. Torpedo, self-propelled (1866,UK)
279. Dynamo, direct current, self excited (1867,Belgium)
280. Hay carrier (1867,US)
281. Paper, wood pulp, sulphite process (1867,US)
282. Chlorine, Deacon process (1868,UK)
283. Concrete, reinforced (1868,France)
284. Dynamite (1868,Sweden)
285. Typewriter, first practical (1868,US)
286. Airbrake (1869,US)
287. Alizarin, synthetic (1869,Germany)
288. Voting machine, electric (1869,US)
289. Celluloid, pyroxyline (1870,US)
290. Oleomargarine (1870,France)
291. Lathe, screw cutting, fully automatic (1870,US)
292. Rectifier, crystal (1870,Germany)
293. Photographic dry plate, silver bromide, gelatin emulsion (1871,UK)
294. Railway, funicular (1871,Switzerland)
295. Tide predictor machine (1872,UK)
296. Coupler, automatic, railway (1873,US)
297. Typewriter, commercial (1873,US)
298. Insecticide, DDT (1874,Germany)
299. Telegraph, wire, quadruplex (1874,US)
300. Wire, barbed, machine (1874,US)
301. Reaper, self-binding, twine (1875,US)
302. Refrigeration machine (1875,Switzerland)
303. Stock ticker (1875,US)

304. Wire, barbed, improved (1875,US)
305. Electric railroad (1875,Germany)
306. Automobile, gasoline (1875,Germany)
307. Automobile, gasoline (1875,Austria) <contested>
308. Fuse, lead (1875,US)
309. Glass, hardened (1875,France)
310. Pneumatic riveting (1875,US)
311. Vaseline (1875,US)
312. Bicycle, modern rear wheel drive, "safety" (1876,UK)
313. Cigarette, continuous machine (1876,US)
314. Harmonic analyzer, mechanical (1876,UK)
315. Photo engraving (1876,France)
316. Telephone (1876,US)
317. Torpedo, dirigible (1876,UK)
318. Engine, internal combustion, four-cycle (1876,Germany)
319. Microphone (1877,US)
320. Phonograph (1877,US)
321. Cultivator, disc (1878,US)
322. Lamp, incandescent, commercial, carbon filament (1878,US)
323. Anthrax vaccine (1879,France)
324. Cream separator (1879,Sweden)
325. Engine, internal combustion two-stroke (1879,Germany)
326. Tunneling, compressed air (1879,US)
327. Indigo, synthesis (1880,Germany)
328. Optical glass, improved (1880,Germany)
329. Elevator, electric (1880,Germany)
330. Photophone (1880,US)
331. Thermometry, precise (1880,France)
332. Photography, high speed (1880,US)
333. Photography, high speed (1880,UK)
334. Serum therapy (1880,France)
335. Button-hole machine (1881,US)
336. Camera, hand, plate (1881,US)
337. Color photography, trichromatic half-tone plates (1881,US)
338. Electric cell, wet, commercial (1881,France)
339. Submarine, improved (1881,Sweden)
340. Electric power, hydroelectric central (1882,US)
341. Electric power, steam engine (1882,US)
342. Printing press, 2 revolutions (1883,US)
343. Rayon (1883,UK)
344. Rayon, viscose (1883,UK)
345. Antipyrine (1884,US)
346. Calculating machine, accounting, punch card (1884,US)
347. Cocaine, local anesthesia (1884,Austria)
348. Machine gun, recoil operated (1884,UK)

349. Paper, wood pulp, sulphate process (1884,Germany)
350. Pen, fountain, improved (1884,US)
351. Photographic film, roll (1884,US)
352. Rayon, nitrocellulose (1884,France)
353. Steam turbine, reaction type (1884,UK)
354. Steel alloy, manganese (1884,UK)
355. Television, Nipkow disk (1884,Germany)
356. Trolley car (1884,US)
357. Automobile, differential gear (1885,Germany)
358. Bordeaux mixture, a fungicide (1885,France)
359. Engine, internal combustion, tri-cycle (1885,Germany)
360. Linotype forerunner (1885,US)
361. Motorcycle (1885,Germany)
362. Aluminum, electrolytic process (1886,US)
363. Aluminum, electrolytic process (1886,France)
364. Photo-engraving, half-tone (1886,US)
365. Transformer, alternating current (1886,US)
366. Comptometer (1887,US)
367. Cyanide gold process (1887,UK)
368. Engine, internal combustion, small, high speed (1887,Germany)
369. Gramophone (1887,US)
370. Monotype (1887,US)
371. Record, cylinder (1887,US)
372. Calculating machine, recording, first practical (1888,US)
373. Camera, hand, roll film (1888,US)
374. Dynamo, split phase induction (1888,US)
375. Electric current, polyphase system (1888,US)
376. Meter, induction (1888,US)
377. Photographic film, celluloid (1888,US)
378. Tire, pneumatic, improved (1888,UK)
379. Diathermy, high frequency (1888,France)
380. Crown cork (bottle cap) (1888,US)
381. Radio coherer (1888,France)
382. Steel alloy, Harvey process, hardening steel esp. for armor plate (1888,US)
383. Dial recorder (1889,US)
384. Motion picture camera (1889,US)
385. Steam turbine, impulse type (1889,Sweden)
386. Telephone, automatic (1889,US)
387. Engine, internal combustion, four-cylinder (1890,France)
388. Fingerprinting (1890,France)
389. Lamp, gas mantle (1890,Austria)
390. Rayon, cuprammonium (1890,France)
391. Time recorder (clock) (1890,US)
392. Tractor, first patent (1890,US)

393. Glider (1890,US)
394. Glider (1890,Germany)
395. Color photograph (1891,France)
396. Diphtheria antitoxin (1891,Germany)
397. Engine, internal combustion, forerunner of modern (1891,France)
398. Gun sight, telescopic (1891,US)
399. Petroleum cracking process (1891,UK)
400. Sero-therapeutic inject in man (1891,France)
401. Automobile, electric (1892,US)
402. Lamp, mercury vapor (1892,Germany)
403. Thermos bottle (1892,UK)
404. Wireglass (1892,US)
405. Automobile, gasoline, improved (1892,US)
406. Automobile, gasoline, improved (1892,France)
407. Automobile, gasoline, improved (1892,Germany)
408. Coke oven (1893,Austria)
409. Glass, fiber (1893,US)
410. Motion picture projector, kinetoscope (1893,US)
411. Diesel engine (1893,Germany)
412. Antitoxin (1894,Germany)
413. Color photography, ruled screen process (1894,UK)
414. Diphtheria antitoxin, improved (1894,France)
415. Motion picture projector, phantascope (1894,US)
416. Canning of food made safe (1895,US)
417. Hydrogen, liquid (1895,UK)
418. Oxygen from liquid air (1895,Germany)
419. Rayon, acetate (1895,UK)
420. X-ray (1895,Germany)
421. Photoelectricity, practical photo-electric cell (1895,Germany)
422. Airplane, experimental (1896,US)
423. Camphor, synthesis (1896,France)
424. Ore unloader (1896,US)
425. Plow, disc (1896,US)
426. Record, disc (1896,US)
427. Steam turbine, velocity compounded (1896,US)
428. Telegraph, wireless (1896,Italy)
429. Cloud chamber (1896,UK)
430. Airship, rigid (1897,Germany)
431. Cannon, quick-firing (1897,France)
432. Cathode tube, oscillography (1897, Germany)
433. Lamp, Nernst (1897,Germany)
434. Torpedo, radio (1897,US)
435. Welding, thermit process (1897,Germany)
436. Airship, non rigid, gas-powered ascent (1898,France)
437. Krypton (1898,UK)

438. Magnetic recording (1898,Denmark)
439. Neon gas (1898,UK)
440. Submarine, improved (1898,US)
441. Aspirin (1899,Germany)
442. Automobile, magneto (1899,Germany)
443. Hydrogenation catalysts (1899,France)
444. Flotation ore extraction (1899,US)
445. Cellophane (1900,Switzerland)
446. Nitric acid by ammonia oxidation (1900,Germany)
447. Steel, electric process (1900,France)
448. Telephone, loaded line (1900,US)
449. Tractor, caterpillar (1900,US)
450. Motion picture synchronized with phonograph (1901,France)
451. Steel alloy, high speed (1901,US)
452. Telegraph, wireless, trans-atlantic signals (1901,Italy)
453. Rectifier, mercury arc (1902,US)
454. Telephone radio (1902,US)
455. Airplane, first flight (1903,US)
456. Airplane and aileron (1903,US)
457. Airship, station (Neuilly, Fr.) (1903,France)
458. Alternator, high speed (1903,US)
459. Barbital, sedative (1903,Germany)
460. Depth charge (1903,Sweden)
461. Glass, window, machine blown process (1903,US)
462. Glider, first flights (1903,US)
463. Glider, first flights (1903,Germany)
464. Dynamo, automatic acceleration (railway) (1904,US)
465. Telephotography, wire (1904,Germany)
466. Glass, safety (1905,UK)
467. Gyroscope, compass and stabilizer (1905,US)
468. Radio, direction aerial, horizontal (1905,Italy)
469. Radio tube, diode, first practical (1905,UK)
470. Glass bottle machine, automatic (1905,US)
471. Resins, synthetic, baselite (1906,US)
472. Blood transfusion (1907,US)
473. Color photography, auto-chrome process (1907,France)
474. Helicopter (1907,France)
475. Helium, liquid (1907,Netherlands)
476. Radio tube, triode (1907,US)
477. Lens achromatic fused bifocal (1908,US)
478. Novocaine (1908,UK)
479. Radio activity counter (1908,UK)
480. Silencer, firearm (1908,US)
481. Duralumin (1909,Germany)
482. Glass, laminated (1909,France)

483. Salvarsan (1909,Germany)
484. Telegraph, wire, multiplex (1910,US)
485. Ammonia process (1910,Germany)
486. Hydrogenation of coal (1910,Germany)
487. Cotton picker, mechanical (1910,US)
488. Air conditioning, modern (1911,US)
489. Filter, electric (1911,US)
490. Lamp, neon (1911,France)
491. Seaplane (hydroplane) (1911,US)
492. Automobile, self-starter (1912,US)
493. Piezo-electric oscillator (1912,US)
494. Radio tube, high vacuum (1912,US)
495. Seaplane, flying boat (1912,US)
496. Telephone amplifier (1912,US)
497. Lamp, incandescent, gas-filled (1913,US)
498. Lamp, incandescent, tungsten, ductile (1913,US)
499. Motion picture, sound (1913,US)
500. Radio receiver, cascade tuning (1913,US)
501. Radio receiver, heterodyne (1913,US)
502. Radio tube, multi-grid (1913,US)
503. Radio tube, triode transmitter (1913,US)
504. Rubber, butadiene (1913,Germany)
505. Ship, electric propulsion (1913,US)
506. Gasoline, from liquefied coal (1914,Germany)
507. Photographic film, pan-chromatic (1914,US)
508. Tank, military (1914,UK)
509. Dynamo, hydrogen cooled (1915,US)
510. Glass, heat resistant (Pyrex) (1915,US)
511. Radio, the oscillator (1915,US)
512. Searchlight, high-intensity arc (1915,US)
513. Telephone, radio, long distance (1915,US)
514. Radio broadcasting (1916,US)
515. Steel, stainless (1916,UK)
516. X-ray tube (1916,US)
517. Engine, supercharger (1917,US)
518. Filter, wave (1917,US)
519. Sonar, detection system (1917,France)
520. Submarine detector (1917,US)
521. Mass spectroscope (1918,US)
522. Quinine, synthetic (1918,Germany)
523. Time system, self-regulating, electric (1918,US)
524. Lubricants, high pressure (1919,UK)
525. Mass spectrograph (1919,UK)
526. Radio altimeter (1919,US)
527. B.C.G. tuberculosis serum (1920,France)

528. Microphone, high quality (1920,US)
529. Telephone, voice reinforcement (1920,US)
530. Autogyro (1920,Spain)
531. Glass plate, semi-continuous manufacture (1920,Germany)
532. Heat of sea, utilized (1920,France)
533. Television, first demonstration (1920,UK)
534. Television, first demonstration (1920,US)
535. Lacquers, synthetic (1921,US)
536. Power cable, oil filled (1921,Italy)
537. Anesthesia, ethylene (1922,US)
538. Gasoline, lead ethyl (1922,US)
539. Radar (1922,US)
540. Radio receiver, super-heterodyne (1923,US)
541. Rectifier, copper-oxide (1923,US)
542. Television, iconoscope (1923,US)
543. Foods, frozen process (1923,US)
544. Lens, fused bifocal (1924,US)
545. Loudspeaker, dynamic (1924,US)
546. Phonograph, orthophonic (1924,US)
547. Welding, atomic hydrogen (1924,US)
548. Photo telegraphy (1925,US)
549. Radar, pulse technique of ionosphere investigation (1925,US)
550. Gasoline from hydrogenation of carbon oxides (1925,Germany)
551. Methanol, synthesis (1925,France)
552. Radioactivity counter, improved (1925,UK)
553. Engine, internal combustion, compound (1926,US)
554. Differential analyzer (1927,US)
555. Color photography, commercial (1928,US)
556. Iron lung (1928,US)
557. Plasmochin (anti-malarial) (1928,Germany)
558. Radio beacon (1928,US)
559. Teletype (1928,US)
560. Television, image dissector tube (1928,US)
561. Coaxial cable system for high frequency signals (1929,US)
562. Electrostatic generator (1929,US)
563. Penicillin (1929,UK)
564. Refrigerator, low-boiling fluorine compounds (Freon) (1930,US)
565. Rubber, neoprene (1930,US)
566. Vitamin C, synthesized (1930,US)
567. Vitamin C, synthesized (1930,UK)
568. Vitamin C, synthesized (1930,Switzerland)
569. Cyclotron (1931,US)
570. Resins, melamine formaldehyde (1931,US)
571. Vitamin A2 synthesized (1931,Switzerland)
572. Electron microscope (1932,Germany)

573. Polaroid (1932,US)
574. Rectifier, ignition mercury arc (1932,US)
575. Atabrine (antimalarial) (1933,Germany)
576. Dynamo, alternating current, high capacity (railroad) (1933,US)
577. Motion picture, three dimensional (1933,US)
578. Radio, frequency modulation (1933,US)
579. Sulfanilamide (1934,Germany)
580. Cortisone, compound E forerunner of (1935,US)
581. Radar, improved (1935,UK)
582. Waveguide (1936,US)
583. Jet engine (1937,UK)
584. Nylon (1937,US)
585. Memory machine (1938,US)
586. Radar, signals bounced back from moon (1938,UK)
587. Rubber, butyl (1938,US)
588. Shoran (1938,US)
589. Sulfapyridine (1938,UK)
590. Glass, silica (1939,US)
591. Loran (electronic navigation guide) (1940,US)
592. Jet plane (1940,Italy)
593. Jet plane (1941,UK)
594. Sulfadiazine (1940,US)
595. Toluene, synthetic (1940,US)
596. Vitamin, biotin, synthesized (1940,US)
597. Vitamin, folic acid, synthesized (1940,US)
598. Teleran (aviation) (1941,US)
599. Atomic pile (1942,US)
600. Guided missile (1942,Germany)
601. Electron microscope, desk type (1943,US)
602. Electron spectrometer (1944,US)
603. Atomic bomb (1945,US)
604. Rain-making, nucleation technique for (1945,US)
605. Streptomycin (1945,US)
606. Synchrotron and synchro-cyclotron (1945,US)
607. Transistor (1946,US)
608. Uranium, purification for atomic uses (1946,US)
609. Meson, production of (1947,US)
610. Scintillation counter (1947,US)
611. Aureomycin (1948,US)
612. Television, image amplifier tube (1948,US)
613. Neomycin (1949,US)
614. Contaben (1950,Germany)